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Hotwire measurements of the turbulent flow into a cascade of controlled-diffusion compressor blades

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HOTWIRE MEASUREMENTS OF THE TURBULENT FLOW INTO A CASCADE OF CONTROLLED-DIFFUSION COMPRESSOR BLADES

by

Bryce Edwin Wakefield

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Thesis Advisor: Garth V. Hobson

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Turbulence measurements near the leading edge of a compressor stator were made in a subsonic cascade wind tunnel with a hotwire system. Using a single hotfilm probe, velocity and turbulence distortion data were obtained about the leading edge of the Controlled-Diffusion (CD) blades in order to verify Laser Doppler Velocimetry (LDV) data taken in earlier studies. Measurements were conducted at a Mach number of .25, a Reynolds number of 711000 and an inlet flow angle of 48 degrees. Turbulence profiles obtained in the pitchwise direction were found to be in good agreement with previous LDV measurements. These data indicated a localized increase in turbulence around the leading edge due to the interaction of the free-shear layer with the inlet turbulence. This free-shear layer extends over the separation bubble, which forms on the suction side of the blades' leading edge.

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HOTWIRE MEASUREMENTS OF THE TURBULENT FLOW INTO A CASCADE OF CONTROLLED-DIFFUSION COMPRESSOR BLADES

by

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

Turbulence measurements near the leading edge of a compressor stator blade were made in a subsonic cascade wind tunnel with a hotwire system. Using a single hotfilm probe, velocity and turbulence distortion data were obtained about the leading edge of the Controlled-Diffusion (CD) blades in order to verify Laser Doppler Velocimetry (LDV) data taken in earlier studies. Measurements were conducted at a Mach number of .25, a Reynolds number of 711000 and an inlet flow angle of 48 degrees. Turbulence profiles obtained in the pitchwise direction were found to be in good agreement with previous LDV measurements. These data indicated a localized increase in turbulence around the leading edge due to the interaction of the free shear layer with the inlet turbulence. This free shear layer extends over the separation bubble, which forms on the suction side of the blades' leading edge.

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Last, but certainly not least, very special thanks goes to my wife, Carol. You are now and forever will be my cornerstone. Your full support, understanding, love and many sacrificies were instrumental in the completion of this work. We did this one together. Love you.

I. INTRODUCTION

A. BACKGROUND

The continuing effort to predict off-design performance and stalling behavior of compressor blades during the design phase has prompted studies in characterizing the flow around the leading edge separation bubbles of blades in cascade. Leading edge separation affects fan and compressor stall by giving rise to decreased mean flow levels and increased turbulence intensities.

Walraevens and Cumpsty [Ref. 1] conducted hotwire tests on the leading edge separation bubble using a single aerofoil (circular and elliptical shaped leading edges) to simulate the range of conditions found on compressor blades. Results indicated that a raised level of freestream turbulence can cause shortening, even elimination of the bubble and an increase in the magnitude of the suction spike. A complete understanding of the unsteady separation and vortex shedding processes associated with leading edge separation will assist in the further development of computer codes to accurately predict off-design and stall of compressor blades [Ref. 2].

B. CONTROLLED-DIFFUSION (CD) BLADING

CD blades are designed analytically to avoid suction surface boundary layer separation and ensure stable compressor

operation over a wider range of inlet conditions. The blades' rounded leading edges, however, can cause leading edge separation at all incidences. The approaching inlet freestream turbulence intensity is significantly magnified around the leading edge, which affects the formation of the separation bubble.

The Naval Postgraduate School's (NPS) low speed cascade wind tunnel was configured with the mid section of a CD stator blade designed by Sanger [Ref. 3] at NASA Lewis Research Center. Previous studies with the present CD blading include the work by Koyuncu [Ref. 4] who conducted pressure probe tests at inlet flow angles from 24.3 to 47.2 degrees to establish on- and off-design blade losses. Subsequently, Dreon [Ref. 5] made wake measurements using a calibrated pneumatic probe at various positions moving downstream through the wake for air inlet angles of 40.3 and 43.4 degrees. The data showed that the near wake was asymmetric. The axial velocity ratios (AVR's) for these inlet flow angles were 1.062 and 1.042 respectively. The measured blade surface pressures gave no evidence of flow separation. A more detailed study of the complete flow field through the CD blading was performed by Elazar [Ref. 6], who obtained LDV measurements of the flow through the passage formed by adjacent blades, of the boundary layers, which developed in the blade surfaces and of the near wake development. Hotwire measurements were obtained by Baydar [Ref. 7], in the wake, to verify Elazar's LDV

measurements. Classick [Ref. 8] improved the data acquisition and reduction process for pressure probe measurements using new computer hardware. He made demonstration measurements at an inlet flow angle of 48 degrees. These measurements produced an AVR of 1.108. No flow separation occurred at this high incidence. Armstrong [Ref. 9] also made measurements at a 48 degree inlet flow angle. Using a five-hole conical pneumatic probe and software and procedures developed by Classick, he measured the mass-averaged flow losses, AVR and wake CP static to be 0.1014, 1.016 and 0.3851, respectively. His objective was to passively reduce the size of the leading edge separation bubble, by slotting a blade's leading edge, thereby, improving performance. Concurrent LDV measurements obtained by Hobson and Shreeve [Ref. 10] indicated levels of distortion of the inlet freestream turbulence upstream of the blades' leading edges. Hobson and Shreeve's work provided the background for the present study.

C. PURPOSE

The aim of the present study was to repeat Hobson and Shreeve's experiment using a hotwire system in an attempt to verify the LDV measurements of distortion of the inlet freestream turbulence upstream and near the blades' leading edges. For an inlet freestream turbulence intensity of approximately 1.5%, they measured a localized increase in turbulence, in excess of 10%, at a pitchwise location 1% chord

ahead of the leading edge. The turbulence increased as the leading edge was approached; and, the locus of points of maximum turbulence approached the leading edge at right angles to the stagnation streamline.

II. TEST FACILITY

A. CASCADE WIND TUNNEL

The NPS subsonic cascade wind tunnel, as shown in Figure 1, was used for the present tests. The test facility configuration was the same as that used by Armstrong [Ref. 9] and Hobson and Shreeve [Ref. 10], with the only exception being the installation of a new set of inlet guide vanes (IGV's) as reported by Webber in Reference 11. A schematic diagram of the wind tunnel and test section are shown in Figure 2. The test section is identified by the Plexiglas window. Surveys are taken upstream of blades 7 and 8. A detailed description of the facility, test section and CD blading was fully documented by Sanger and Shreeve [Ref. 12]. The tunnel was adjusted for an inlet flow angle of 48 degrees. A detailed description of the tunnel adjustment process and operation is contained in Appendix A of Murray's thesis [Ref. 13].

B. INSTRUMENTATION

1. Hotwire System

A single probe traverse system was devised and installed to survey around the leading edge of the seventh blade. A TSI model 1210-20 single sensor hotfilm mounted in a Model TSI 1150 probe support and a Model TSI 1152BF right angle holder were inserted into a United Sensor Corporation probe holder. The probe holder was mounted to a manual blade-to-blade traverse table to allow pitchwise movement. The

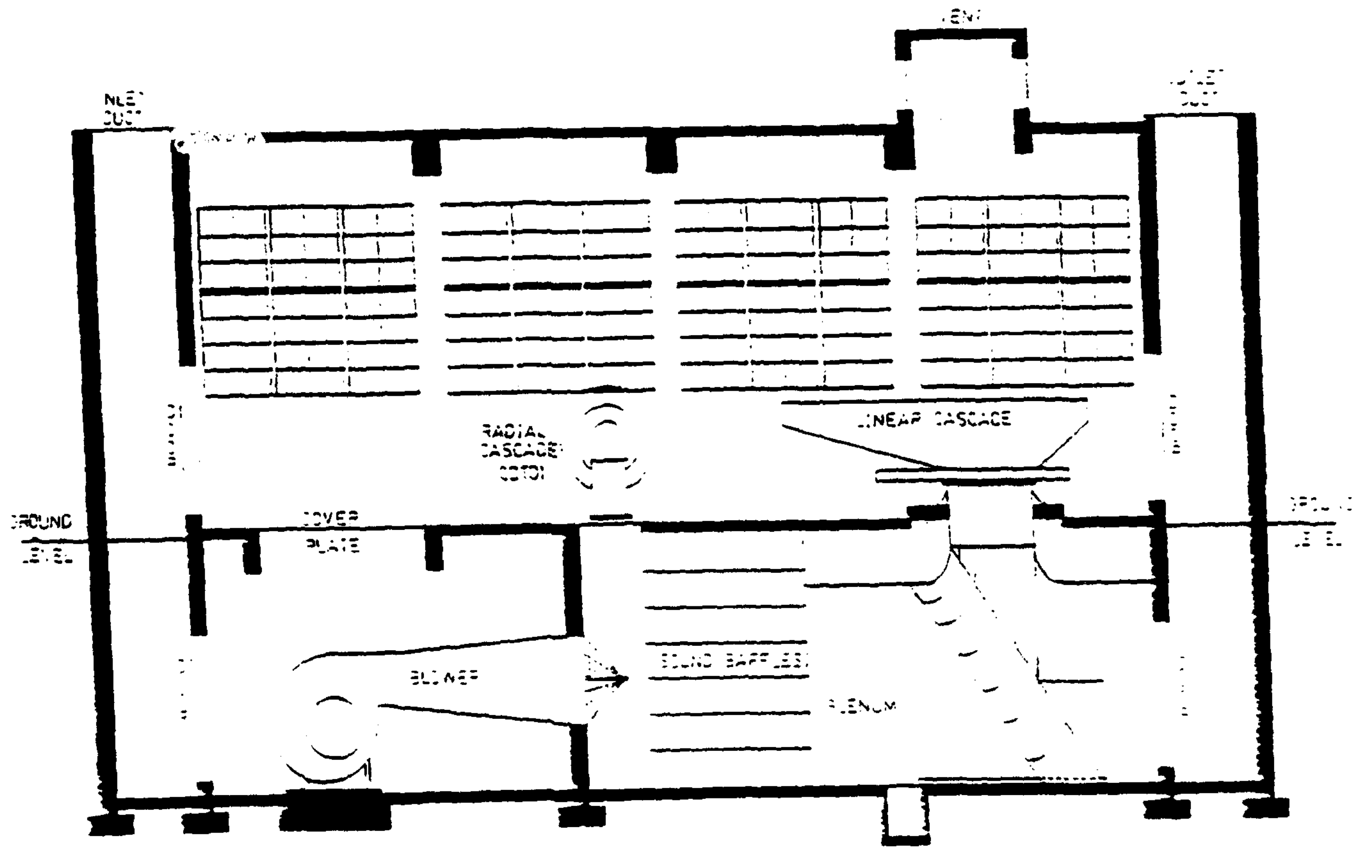


Figure 1. Linear Cascade Wind Tunnel Test Facility

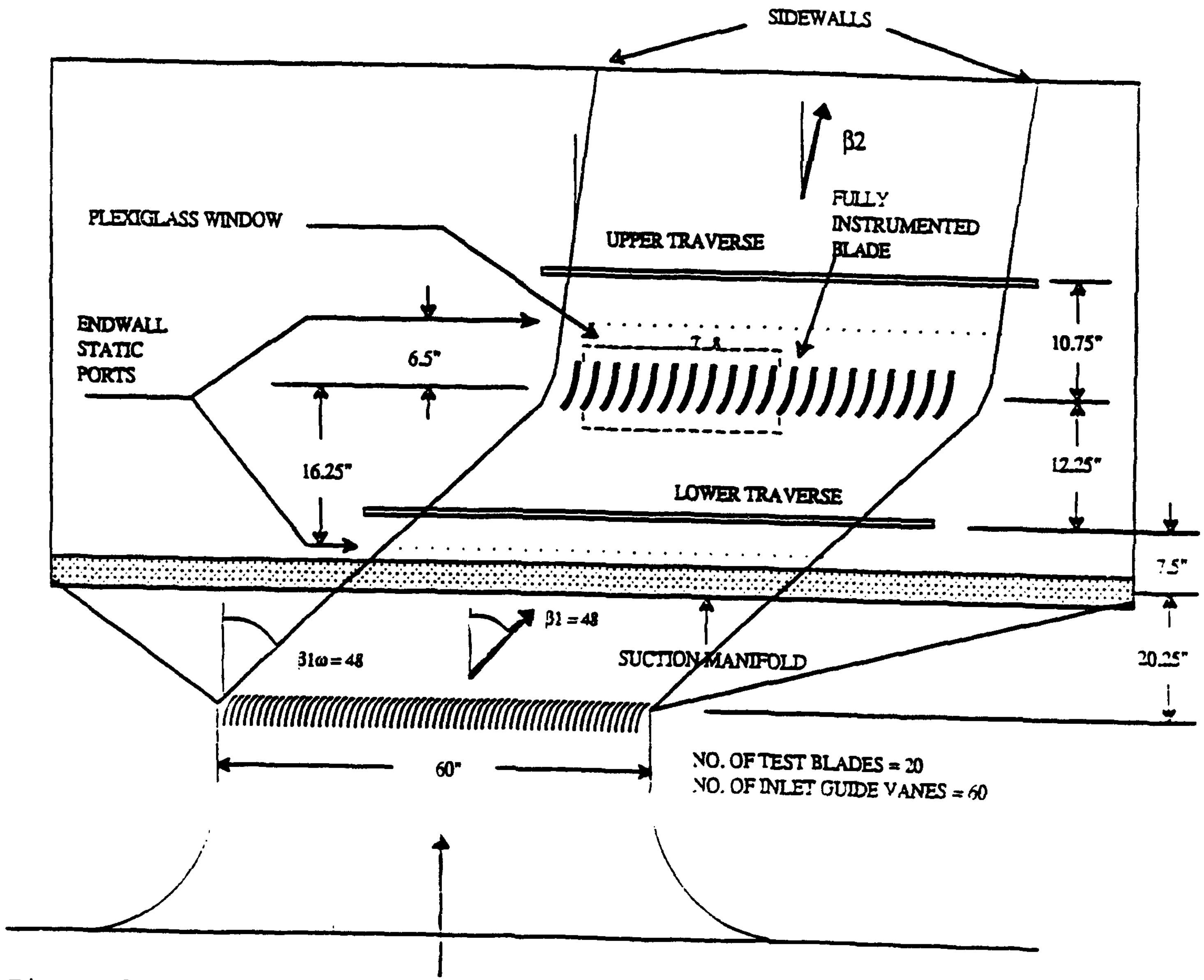


Figure 2. Subsonic Cascade Wind Tunnel and Test Section

traverse mechanism was mounted to the frame of the north wall of the tunnel. The sensor probe set-up and traverse arrangement are shown in Figure 3.

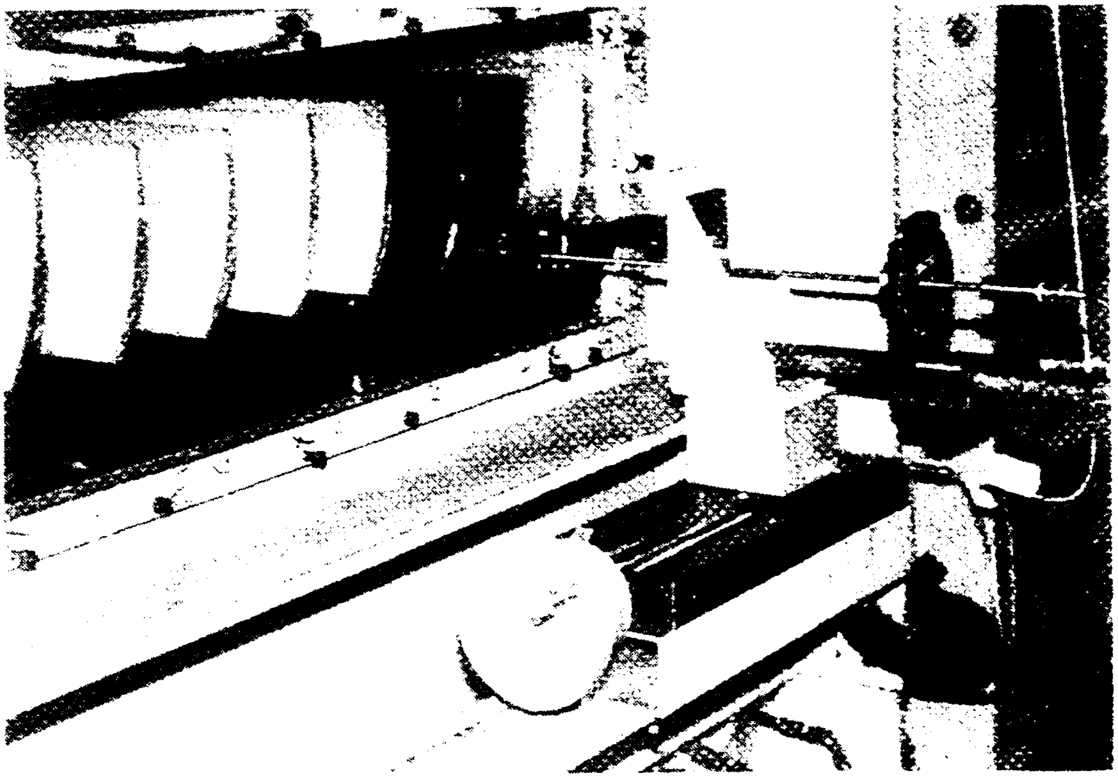
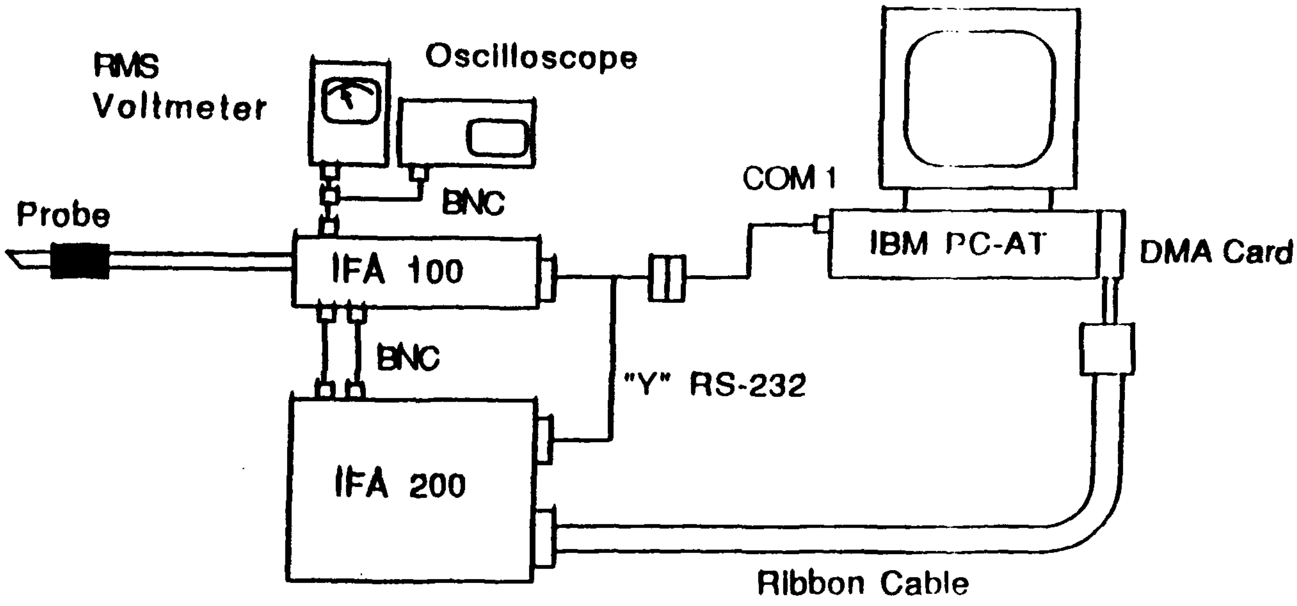
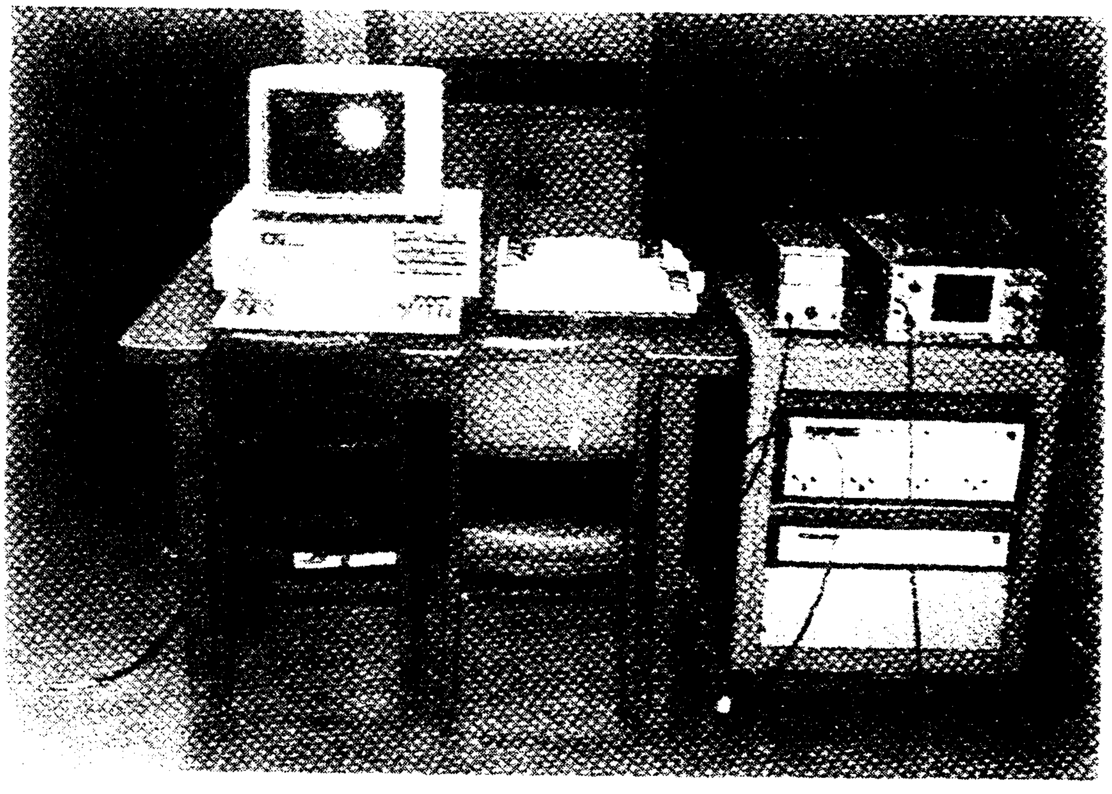


Figure 3. Single Probe Traverse System

The hotwire system, as shown in Figure 4, consisted of the probe, the TSI IFA 100 Anemometer, TSI IFA 200 Digitizer, an IBM PC-AT, printer, RMS voltmeter and an oscilloscope (O-scope). The analog signals from the probe were sent to the IFA 100, which contained the anemometer bridge and servo amplifier. The analog signal was sent from the IFA 100 to the IFA 200 via a BNC cable. The IFA200 digitized the signal and sent it to the computer via a ribbon cable connected to the Direct Memory Access (DMA) card. The digitized data were



a) Schematic Diagram



b) Test Set-up

Figure 4. Hotwire System

converted to velocities using the calibration information. Concurrently, the data were corrected for effects of temperature on the velocity. The O-scope and RMS voltmeter were used for visual observation and manual recording of the flow's turbulence levels. The printer provided a hardcopy of the processed data and graphs.

The TSI Data Analysis Package (DAP) was used to reduce the data from the voltage output of the thermal anemometer system. The IFA thermal anemometry software package contained 6 program packages: Data Acquisition, Statistical Analysis, Traverse Table Control, Spectrum/Correlation, Flow-Field Plotting and Polynominal and King's Law Calibration. These packages are discussed in greater detail in Reference 14. DAP is designed to acquire data with one or more hotwire sensors.

2. Static Pressures

Endwall static pressure measurements for both the north and south walls were measured with the banks of water manometers use by Webber [Ref. 11]. The manometers were also used to monitor the plenum and Prandtl probe total pressures. The Prandtl probe was used to monitor inlet total and static pressure near blade 15.

III. EXPERIMENTAL PROCEDURE

A. TEST SECTION SET-UP AND ADJUSTMENTS

Prior to taking measurements, the inlet flow angle was changed from 44.4 degrees to 48 degrees. The north wall of the wind tunnel was removed. The porous suction slots used by Webber [Ref. 11] were removed and replace with the original solid endwalls. The side-wall angle and inlet guide vanes were set using the procedure documented by Murray [Ref. 13]. After replacing the north wall, the tunnel was started and the tailboards were adjusted to get a uniform downstream static pressure distribution.

B. HOTWIRE/HOTFILM CALIBRATION

Probe calibration was carried out proir to any hotwire or hotfilm measurements. Calibration was performed using the procedures outlined in Appendix A. A more detailed description of the calibration process is contained in Reference 15. The hotfilm probe was installed in the traverse mechanism, at the inlet flow angle, and calibrated midway between blades 7 and 8 at midspan. Six calibration points were chosen. The first calibration point was taken at the tunnel's low speed setting. The second and third were at the medium and fast speed settings. The last three settings were

equally spaced from the fast speed setting (plenum pressure approximately 4.1" water) to the desired operating speed (plenum pressure equal to 12" water). At each speed, as the hotfilm output was sampled, the corresponding pitot-static pressure differential and calibration temperature were recorded and inputed into the calibration data file. The program then fitted these data with a fourth-order polynomial of velocity versus voltage and calculated the calibration coefficients. The coefficients were saved for later use in a file refered to as a "look-up table."

C. SURVEYS

The hotfilm probe was aligned horizontally parallel to the test blades leading edges. All probe surveys for the upper and lower slots were made upstream of the test blades at an inlet flow angle of 48 degrees. The slot's locations are shown in Figure 3.

1. Upper Slot

The initial idea for the upper slot was that the probe could be traversed across (and ahead of) the leading edges of the blades with the probe actually touching the blades. As the probe slid over the leading edges, they provided support opposite to the aerodynamic loading of the flow. However, during preliminary tests, this concept did not support the probe in the pitchwise direction.

The force of the inlet flow pushed the probe in the negative pitchwise direction, causing lags of .3" to .5". The slot also caused the probe to bend below the horizontal plane. To re-establish and maintain positive probe control and positioning during traversing, the support bracket assembly shown in Figure 5 was manufactured. The bracket was designed to be used at both the upper and lower slots. The bracket contained pitchwise and vertical adjustment screws to properly align the probe for the surveys. The probe was aligned by watching reflections of the probe and probe holder in the Plexiglas window and making the necessary fine adjustments with the screws. This process was performed while the tunnel ran at normal operating conditions.

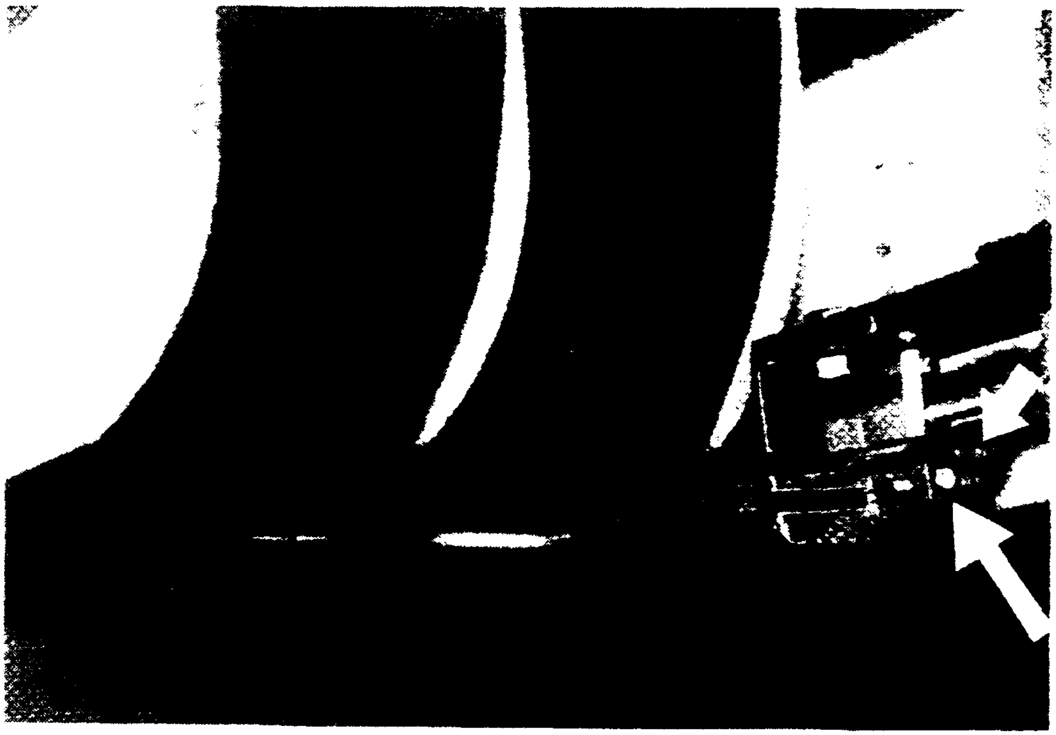


Figure 5. Probe Support Bracket Assembly

Three types of pitchwise surveys were made at the upper slot location. For the first survey, the probe was traversed from the leading edge of blade 7 to the leading edge of blade 5, in increments of .05". The second survey consisted of taking pitchwise measurements at Stations 1a, 1b, 1c, 1d and 1e, plus or minus half an inch about the leading edge of blade 7 in steps of 0.1". The station locations are shown in Figure 6.

2. Lower Slot

In order to take measurements in the lower slot, the two-inch aluminum block shown in Figure 3 was removed. The first survey was a pitchwise traverse from blade 8 to blade 7 in steps of .2". For the second survey, the probe was rotated from horizontal to the inlet flow angle in 2 degree increments, with the probe tip initially at two locations: 1) at the leading edge of blade 7; 2) at the mid passage of blades 7 and 8. The last survey was a pitchwise traverse from blade 8 to blade 6 with the probe at the inlet flow angle.

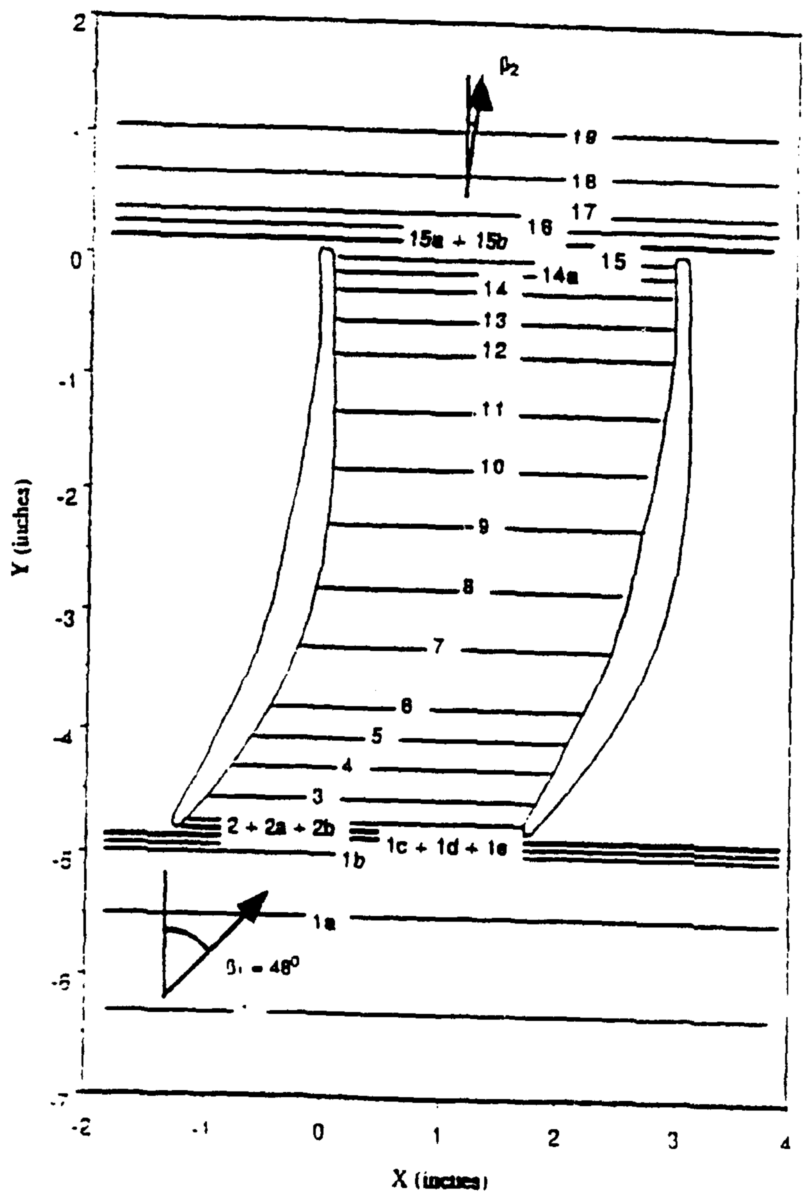


Figure 6. Test Section and Station Locations

Station	Y(in)
1	-6.2920
1a	-5.5000
1b	-5.0000
1c	-4.8960
1d	-4.8440
1e	-4.8180
2	-4.7920
2a	-4.7905
2b	-4.7500
3	-4.5420
4	-4.2920
5	-4.0420
6	-3.7920
7	-3.2920
8	-2.7920
9	-2.2920
10	-1.7920
11	-1.2920
12	-0.7920
13	-0.5000
14	-0.2500
14a	-0.1250
15	0.0000
15a	0.1250
15b	0.1500
16	0.2620
17	0.3620
18	0.6780
19	1.0620

IV. RESULTS AND DISCUSSION

A. INLET BOUNDARY LAYER SURVEYS

Preliminary hotfilm inlet boundary layer surveys were made at 44.4 inlet flow angle to establish the tunnel's freestream turbulence intensity and mean velocity flow profile. These surveys were of the endwall boundary layer on the north wall of the tunnel and extended to midspan. The inlet freestream turbulence was determined to be 1.5%. Complete survey results are listed in Appendix B.

B. UPPER SLOT

1. Pitchwise Traverse Between Blades 7 & 5

The plots of the mean velocity distribution and turbulence intensity are given in Figure 7. The velocity curve shown was non-dimensionlized with respect to the maximum flow velocity measured during the survey.

In general, the velocity profile is qualitatively as expected. The mean flow velocity increased as the probe approached the suction side of the blades and decreased in a similar fashion as the probe traversed past the leading edges. An important observation is that the mean flow velocity shows periodicity. The turbulence intensity profile, on the other hand, does not reflect periodicity in the pitchwise direction. It does, however, indicated the possible existence of localized disturbances near the blades' leading edges. The

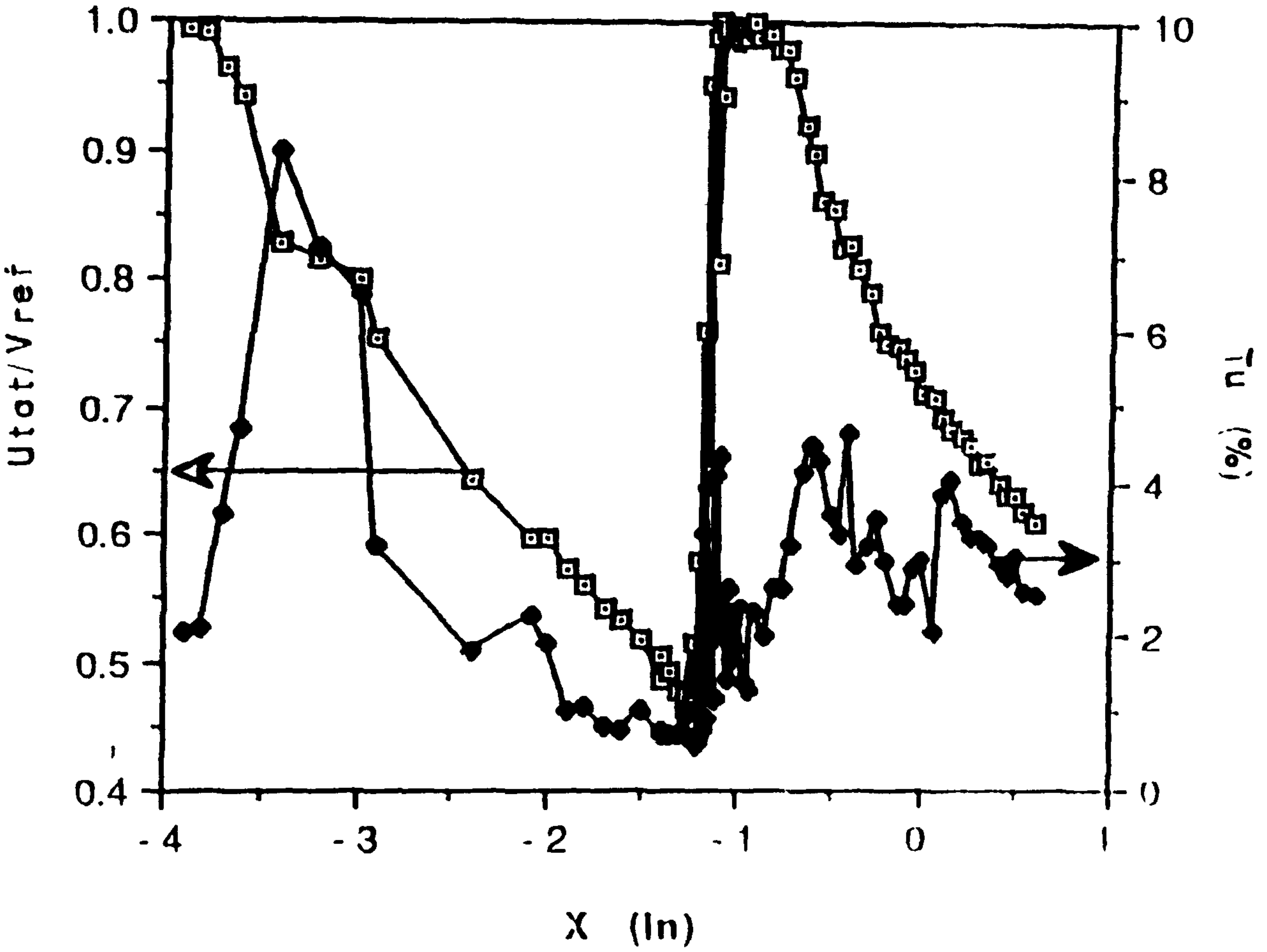


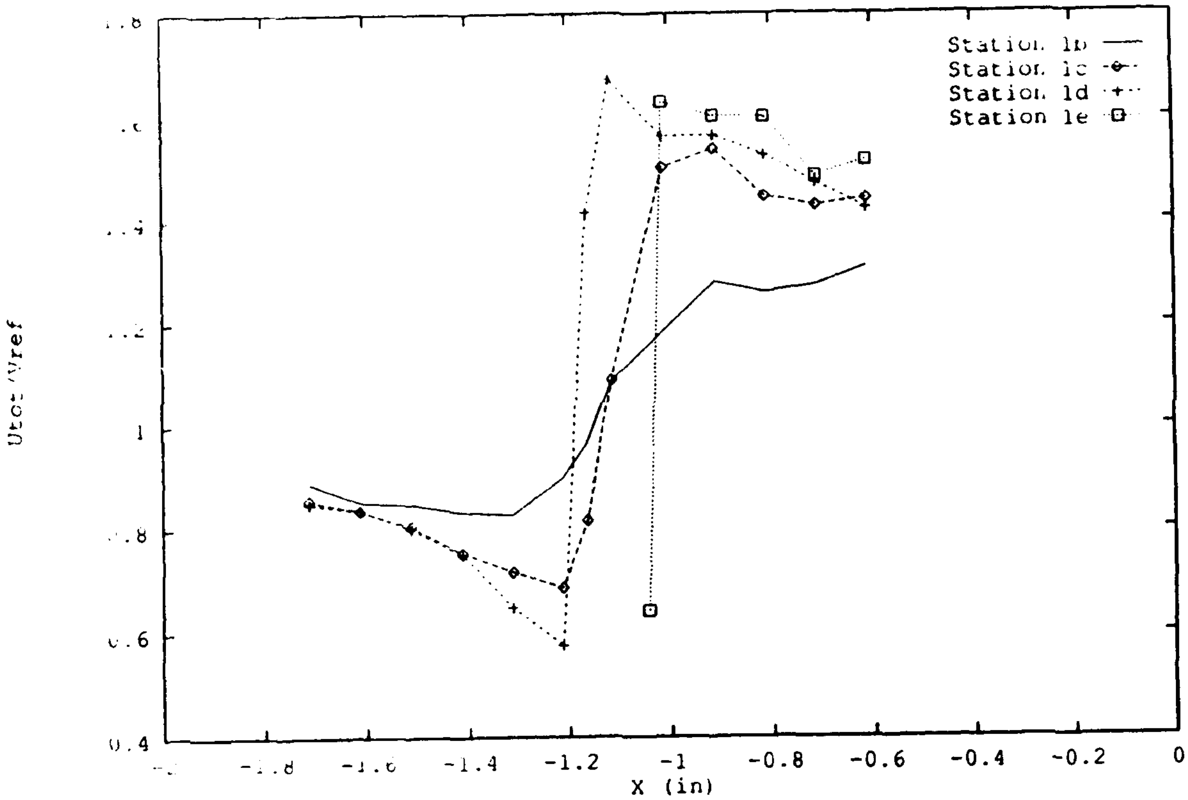
Figure 7. Upper Slot Pitchwise Traverse; Blades 7-5

high levels of turbulence between the blades (in regions -3.7" to -2.75" and -0.75" to 0.5") are attributed to probe incidence effects and possibe vortex shedding. In these regions, the angle of incidence of the probe to the flow was at a maximum. This is evident when considering the velocity vector plot presented by Hobson and Shreeve [Ref. 10].

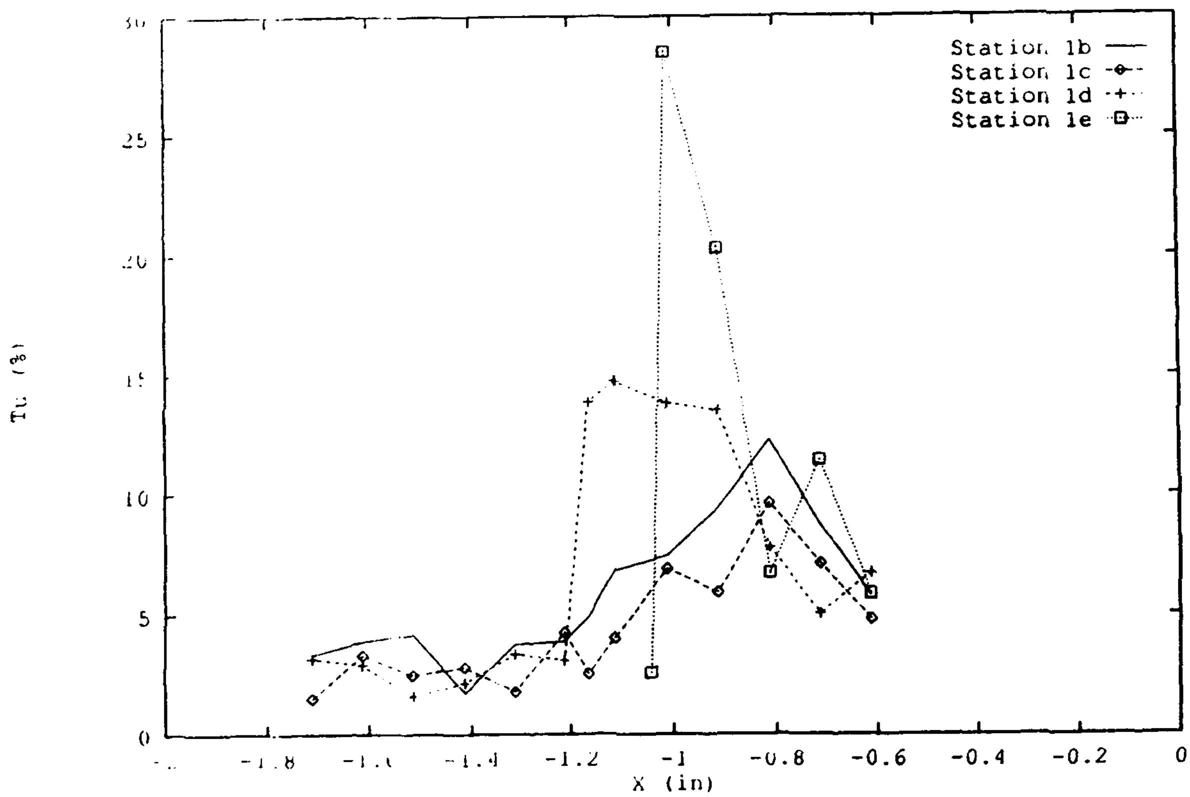
In the region of the leading edge (-1.5" to -0.75"), the flow is approaching the probe near zero incidence. In other words, both the velocity vectors and the probe are horizontal as the flow rounds the blade's leading edge. A distinct and repeatable increase of turbulence intensity was measured in this region. The turbulence intensity rose to 4.4% at x= -1.075", which is directly below the leading edge. It is these areas of high turbulence intensity near the leading edges that are of the most interest and the primary focus of this study.

2. Stations 1b, 1c, 1d and 1e (+ or - 0.5")

The mean flow velocity and turbulence intensity distributions are shown in Figures 8a and 8b. The velocities are non-dimensionalized using the average velocity of station 1a as Vref. Station 1a velocity varied by 5.0%. The velocity profiles show a gradual increase in mean velocity flow on the suction side of the blade as the probe nears the leading edge and a decrease as the probe is traversed passed the blade's leading edge. At station 1e, the mean flow was distorted



a) Non-dimensionalized Velocity



b) Turbulence Intensity

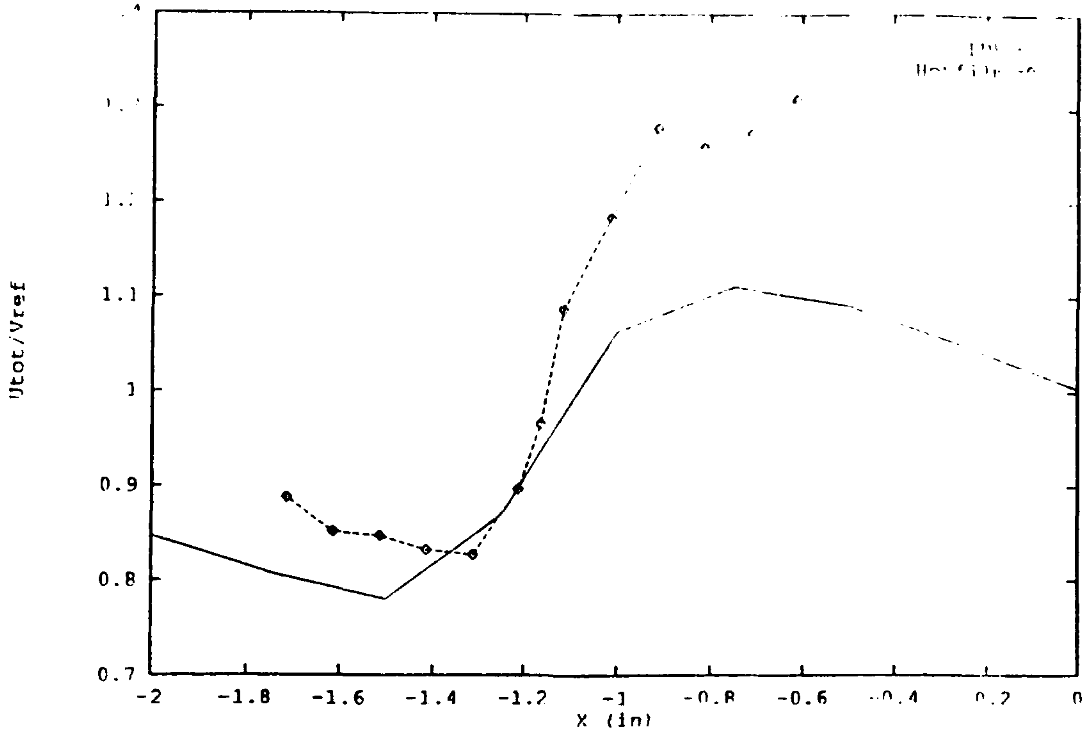
Figure 8. Upper Slot Pitchwise Survey Stations 1b-1e

considerably, with as much as a 60% variation in the total velocity acrosss the passage. Similar results were obtained at the other stations. Station 1b, the station furthest upstream of the blade, experienced 37% variation in total velocity.

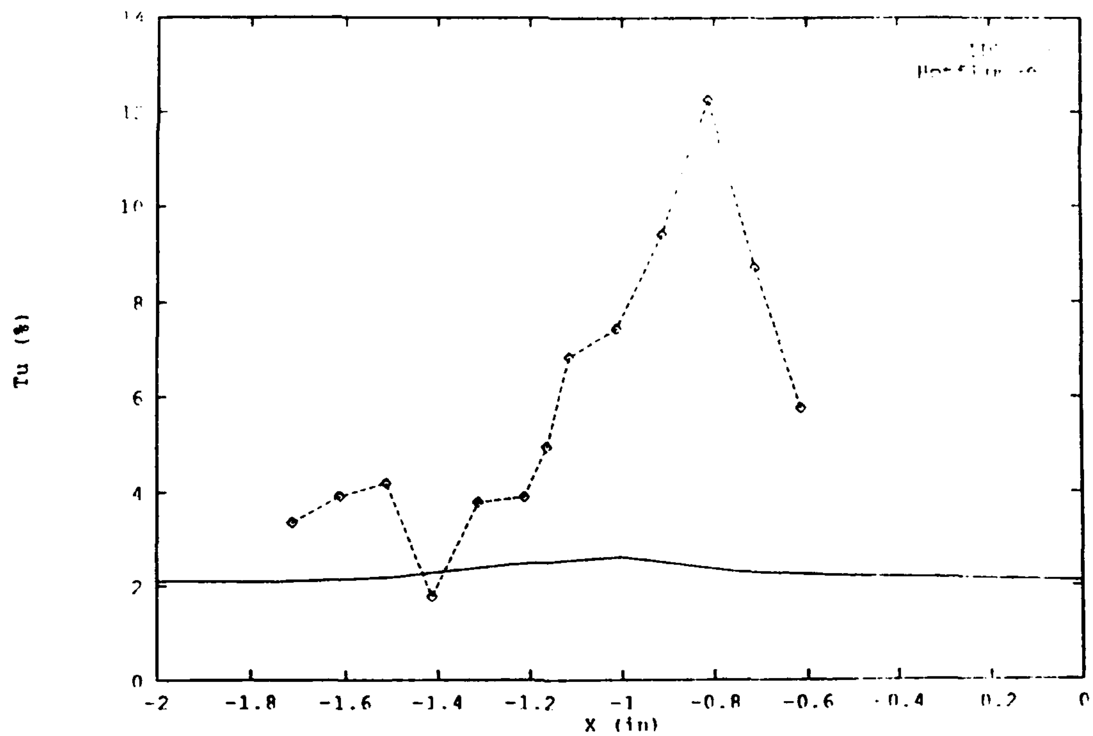
The turbulence intensity profiles show a localized increase in turbulence on the suction side of the blade. As the probe is traversed closer to the blade's leading edge (pitchwise distance and station location), the intensity levels increased by an order of magnitude. The maximum turbulence intensities for stations 1b, 1c, 1d and 1e are 12.5%, 10.0%, 15.0% and 27%, respectively, and were measured near the blade's leading edge. The locus of these points of maximum turbulence appeared to approach the leading edge at right angles to the flow. At stations 1b and 1c the probe experienced a flow field with a near constant velocity vector angle of 48 degrees. Thus, incidence effects most probably accounted for the high turbulence levels measured. At station 1d and 1e, as the leading edge is approached the flow incidence (to the probe) approaches zero. Little or no probe interference effects are felt and the peaks in turbulence are distinct and repeatable.

C. HOTFILM/LDV DATA COMPARISON

Comparisons with LDV data are shown in Figures 9-12. The mean flow profile agrees well. The hotfilm data were non-dimensionalized with repect to the average flow velocity at

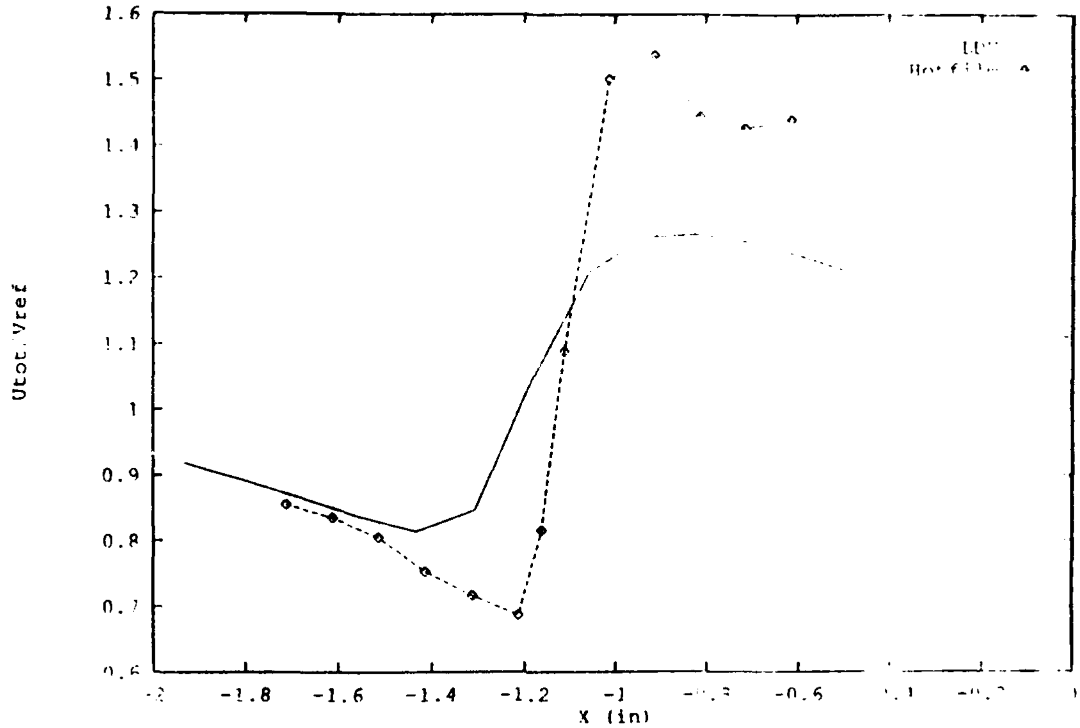


a) Non-dimensionalized Velocity

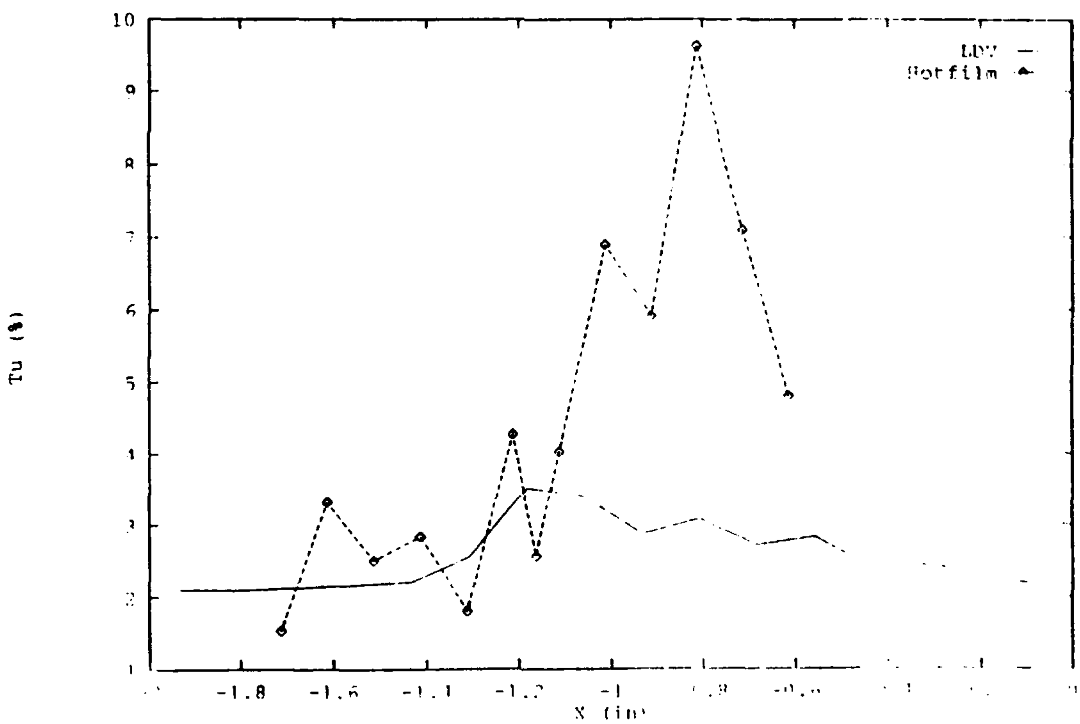


b) Turbulence Intensity

Figure 9. Hotfilm/LDV Comparison at Station 1b

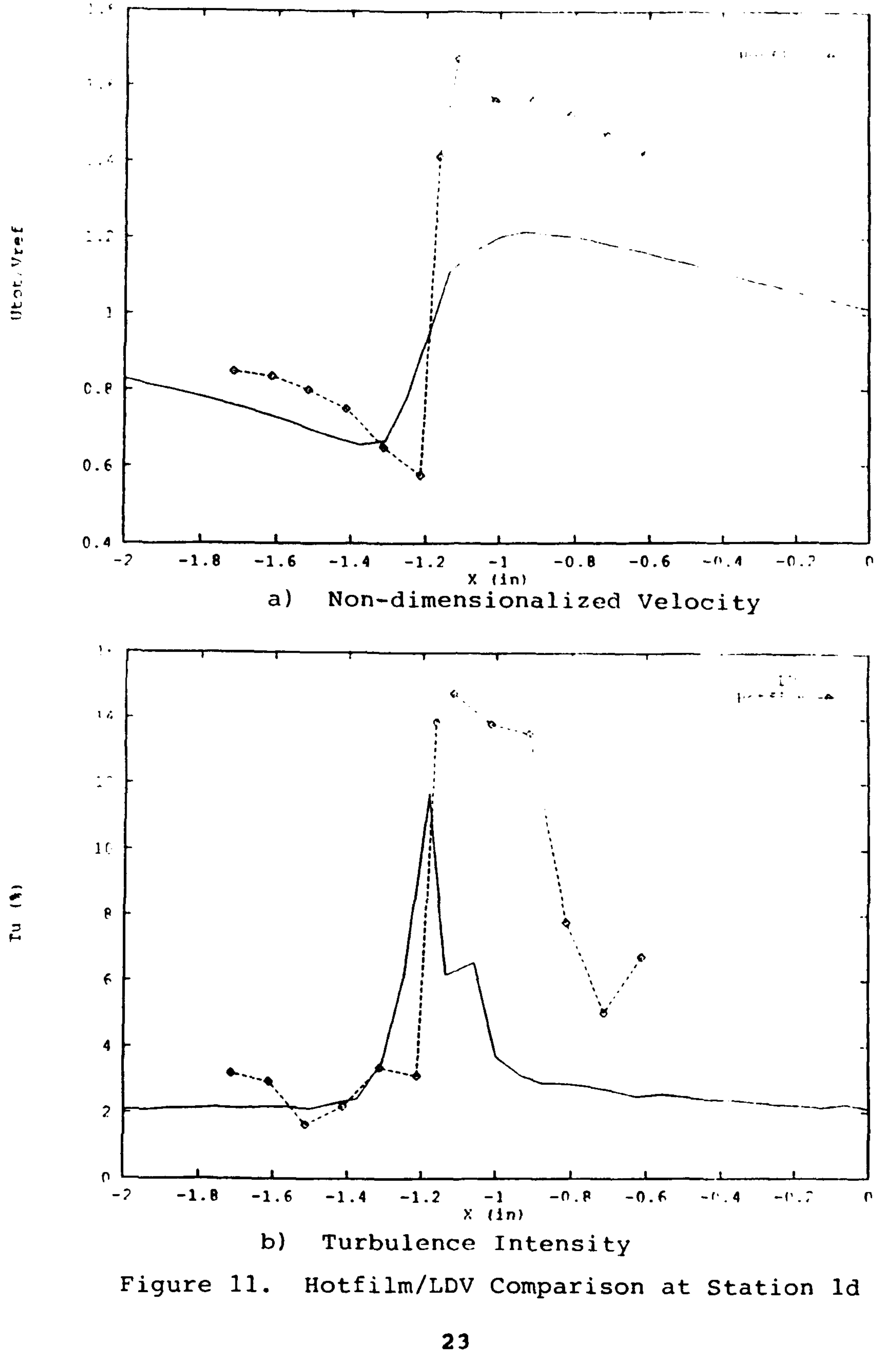


a) Non-dimensionalized Velocity



b) Turbulence Intensity

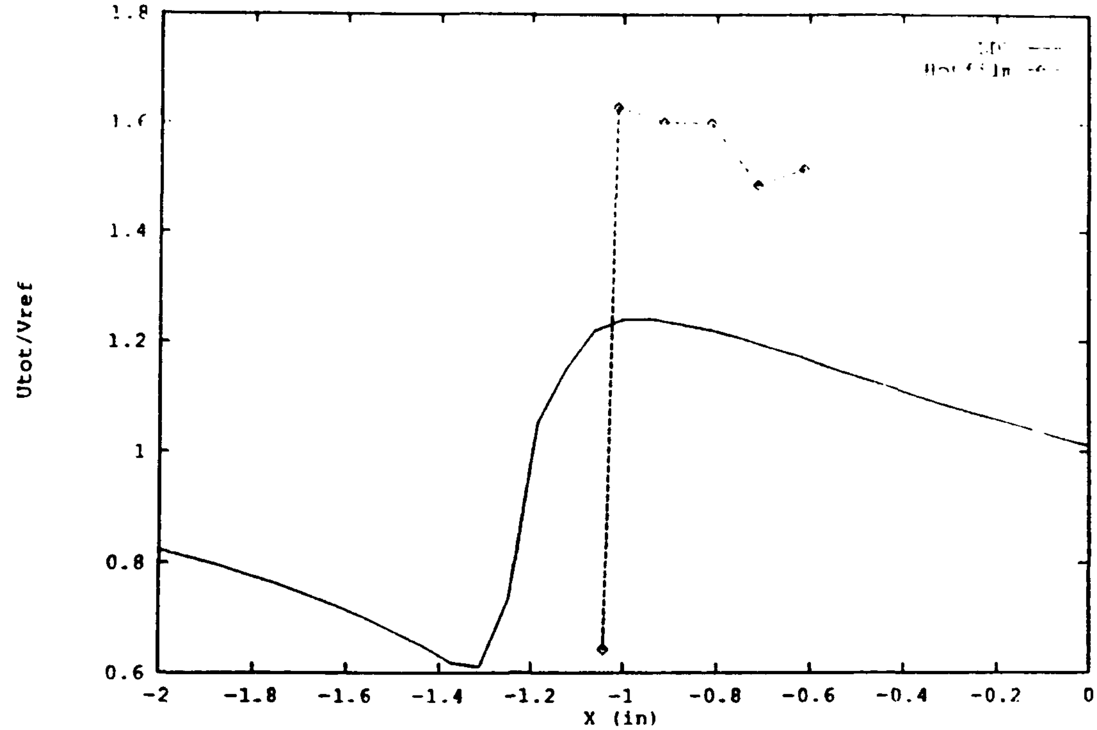
Figure 10. Hotfilm/LDV Comparison at Station 1c



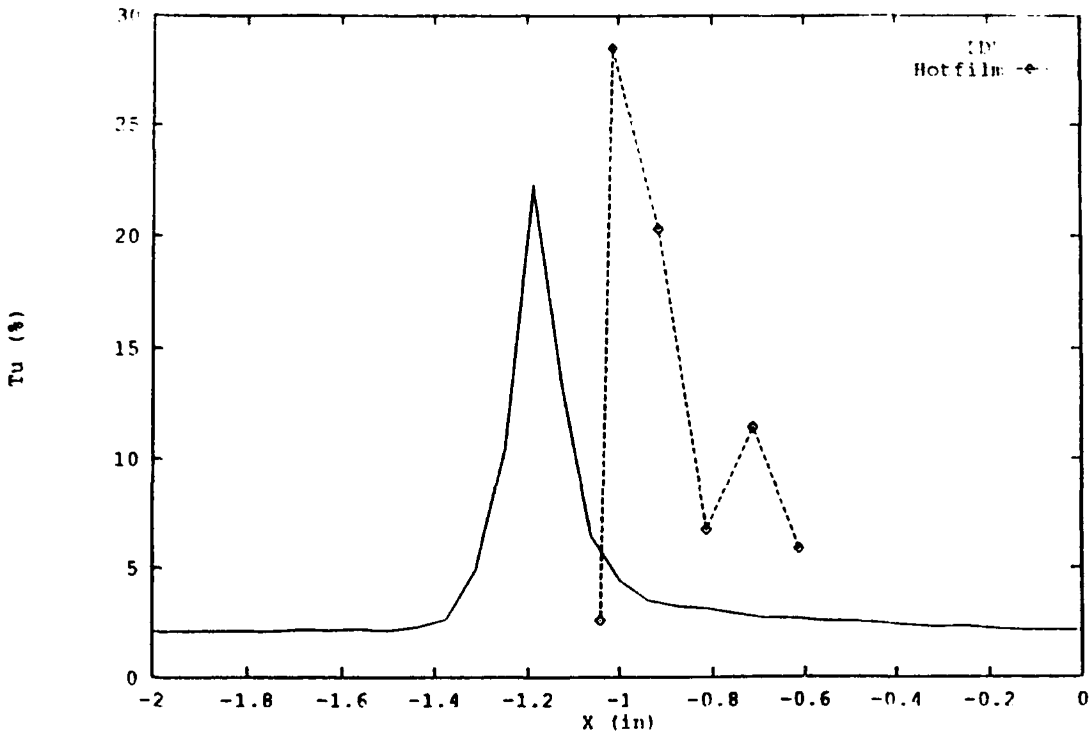
a) Non-dimensionalized Velocity

b) Turbulence Intensity

Figure 11. Hotfilm/LDV Comparison at Station 1d



a) Non-dimensionalized Velocity



b) Turbulence Intensity

Figure 12. Hotfilm/LDV Comparison at Station 1e

station 1a. The LDV system data was normalized with respect to station 1. The velocity at station 1a varied by 5.0%. The velocity at station 1 was uniform. This is one of the reasons why there is a difference between the mean flow profiles as shown in Figures 9a, 10a, 11a and 12a. Significant differences can be seen in the turbulence intensity profiles at stations 1b and 1c. The reason for this was explained in the previous section. At station 1b, the hotfilm turbulence intensity varied from 1.8% to 12.7%. The LDV measured a near uniform turbulence intensity distribution of 2.0%. At station 1c, hotfilm turbulence measurements ranged from 1.5% to 9.8%; whereas, the LDV measurements varied from 2.0% to 3.5%. The following are possible explanations for the differences.

The first reason for the decrease from 12.7% to 9.8% is the decreasing flow incidence to the probe from station 1b to station 1c. A second is the normalization of the velocity. A third reason for the differences is the fundamental differences in the turbulence measurements of the systems. The hotwire system measures both the streamwise and normal fluctuating velocity components. The LDV system measures two individual components (u and v) of the turbulence, which must be combine to obtain a single turbulence value. They were combined using the following equation:

$$Tu = \frac{\sqrt{\left(\overline{u'}\right)^2 + \left(\overline{v'}\right)^2}}{V_{ref}} \quad (1)$$

A fourth possibility is that the particles measured by the LDV do not follow the flow perfectly in these regions close to the blade's leading edge.

The maximum level of turbulence intensity measured by the hotfilm was 27.0% at station 1e (Figure 12b). LDV measured 22.0% at the same station. The reason for the pitchwise shift between data at station 1e is unknown; however, it is felt that the overall levels measured with the two instruments are in reasonable agreement with each other.

D. PITCHWISE TRAVERSE AT INLET FLOW ANGLE BETWEEN BLADES 8&6

Surveys were taken in the lower slot, with the probe at the inlet flow angle, from blade 8 to blade 6 to measure the inlet freestream turbulence intensity. Mean flow velocity and turbulence intensity measurements are shown in Figure 13. The mean velocity distribution is almost uniform, having a 3.0% variation. The turbulence, on the other hand, experienced a 56% variation. The intensity level decreased from 3.4% to 1.8% for one chord length, then increased to 3.1%. The reason for this rise and fall is not known. The results are given for completeness. The 1.8% turbulence level is consistent with previous LDV and hotwire measurements of 1.5%. Wakes from the IGV's are a possible, but not probable, cause of the 3.0% turbulence intensity levels.

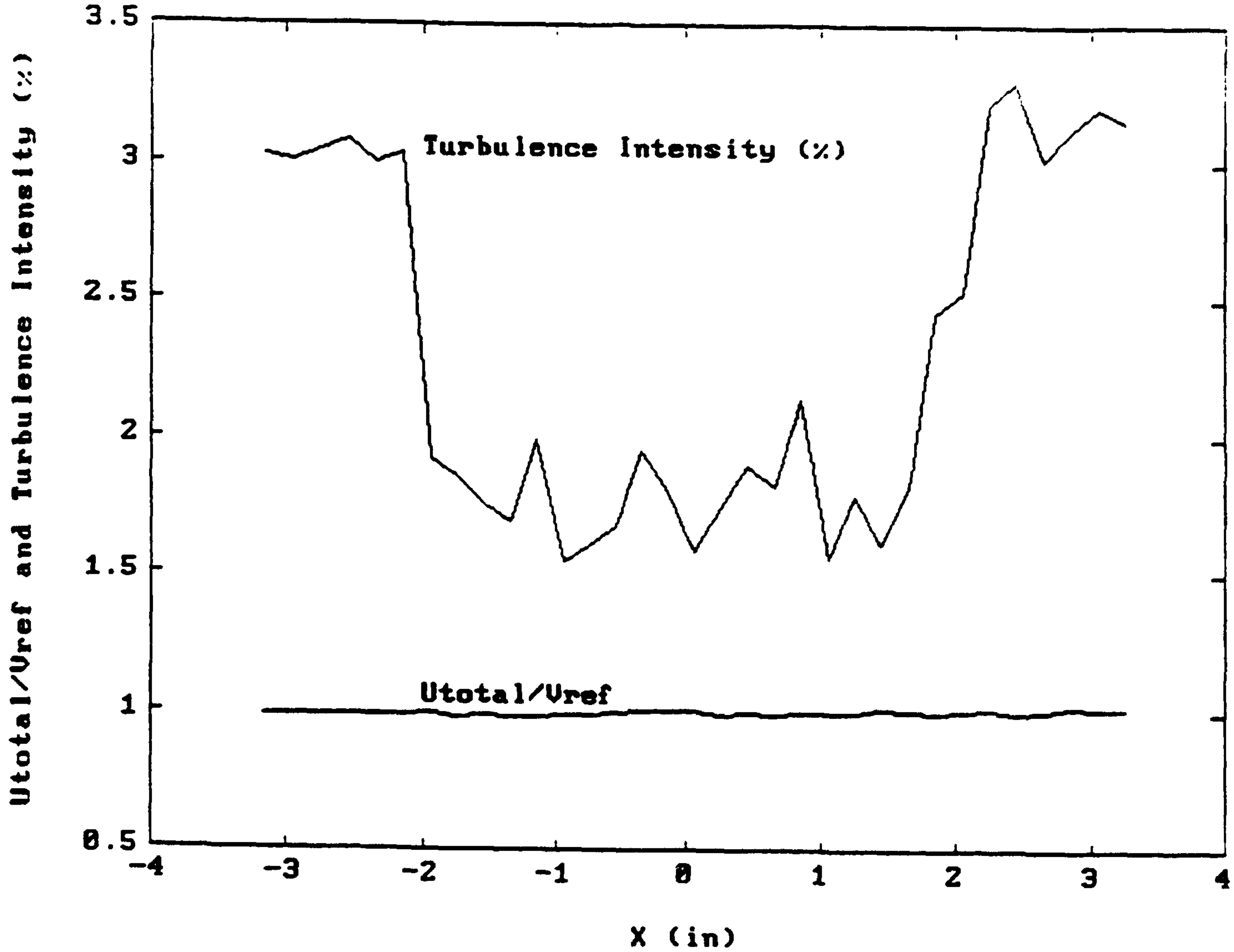


Figure 13. Pitchwise Survey at Inlet Flow Angle;Blades 8-6

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Overall, the aim of this project was achieved since the significant increase in turbulence intensity was measured with the hotwire system and qualitative comparisons were made with previous LDV surveys at the same locations. Other conclusions are listed below.

1. Peaks in the turbulence intensity at the upper slot in blade passage 7-5 occur near the suction side of the leading edges of the blades.

2. The locus of points of maximum turbulence intensity approaches the suction side of the leading edge of the blades at right angles to the flow. This conclusion is from further analysis of the LDV data taken by Hobson and Shreeve [Ref. 10], and somewhat confirmed by Figure 8b..

3. Variation of turbulence intensity levels at the lower slot are unexplained. The 1.8% level is understood; but, the increase to 3.0% is not.

4. Incoming turbulence is approximately 1.5%. The maximum level measured by the hotfilm is 27% at Station 1e. The LDV measured 22.0% at the same station.

B. Recommendations

Because of the unexplained measurements upstream of the blades, additional measurements need to be performed. The following recommendations are made:

1. Verify the inlet flow angle and turbulence profiles the with LDV system.

2. Conduct inlet rake probe surveys to verify the axial velocity ratio (AVR).

3. Increase inlet flow angle to greater than 48 degrees, in an attempt to stall the blades. Repeat hotfilm and LDV measurements.

4. Use a waveform analyzer to determine the energy spectrum levels of the turbulence.

APPENDIX A. HOTWIRE CALIBRATION AND DATA COLLECTION PROCEDURE

This is a step by step procedure for calibrating a hotwire or a hotfilm.

TSI IFA 100/200 Hotwire Anemometer Calibration and Operation

1. Record the atmospheric presssure **Pa** and temperature **Ta.**

2. Measure and record the cable resistance **Rc** with a shorting probe inserted in the probe holder.
   IFA 100 (a) **[RES MEAS]**
   (b) zero with **OPERATE RES** control
   (c) **[RES MEAS]**
   (d) **[ENTER]**

3. Replace the shorting probe with the hotwire/film probe and measure and record the cold resistance **R0** of the probe. Repeat step 2, except **DO NOT** press **ENTER.**

4. Determine the operating resistance of the wire (if this is not given, a resistance of 12 ohms is recommended).
   IFA 100 (a) **[OPERATE RES]**
   (b) Adjust **OPERATE RES** control to set up resistance

5. Bridge and cable compensation.
   IFA 100 (a) **[BRIDGE COMP]**
   (b) Adjust **BRIDGE** control to proper setting for hotwire probe (see IFA 100 manual p. 28).
   (c) **[RUN]** for cable compensation

   First record the no flow voltage of the probe, **EO**; then turn on tunnel to an intermediate speed (**FAST**).
   (d) turn **CABLE COMP** full counterclockwise. **OSC** will come on in the process.
   (e) turn **CABLE COMP** clockwise till **OSC** goes off and watch the Oscilloscope for visual verification of turbulence; then turn **CABLE COMP** 1/4 to 1/2 turn after **OSC** goes off.
   (f) record voltage at **FAST** speed.

6. Preform the frequency response tuning with the square wave generator.

7. Perform the signal conditioning. Estimate **Em** for the channel, and calculate the **Span**, **Offset** and **Gain**. (Do not have to perform this if **Em** is less than 5 volts).

IFA 100 (a) **[OFFSET]**
(b) type in the offset truncated to nearest interger.
(c) **[ENTER]**
(d) **[GAIN]**
(e) type in the Mantissa of the Gain
(f) **[EXPONENT]**
(g) type in the Exponent of the Gain
(h) **[ENTER]**

Bring tunnel back to the lowest speed (or shut down the tunnel).

8. PROBE & CALIBRATION IFA S/W MANUAL AND IBM PC-AT

(a) Data Acquisition Menu

1. <A> Need to run in the Data Acquisition mode first.
2. esc <D>
   a. <E> Diagnostics
   b. <L> Sets the IFA 100 TO [RUN] if it is not.
   c. <R> Remote
   d. <S> Real time read out. Press, esc-esc.
3. esc-esc
4. esc <P> Documentation
   a. <D> Enter probe type and serial #.
5. <M> This returns you the Probe Menu. Can use esc-esc, but this will return you to Main menu and you have to select esc <P> to get back in the Probe Menu.
6. b. <U> Input units.
7. <M>
8. c. <C> Enters ambient conditions. Can also zero Polynomial Coefficents, but is not necessary. Will update automatically.
9. <M>
10. d. <A> Set sample rate.
11. <M>
12. e. <I>
    1) <U> Starts initialization of updated values.
    2) <U> Updated values are displayed.
13. esc-esc
14. esc <Q> Ends Data Acquisition; Returns to Main Menu.

(b) Probe Calibration Menu

1. <P>
2. esc <P> Enter Probe information, ambient conditions and number of calibration points e.g. 5.
3. esc-esc
4. (F1) Records the tunnel plenum pressure and IFA 100 voltage for speed settings (number or points selected for the calibration run). Use the attached sheet to manually record the Plenum Pressure, Pitot Pressure, Temperature, IFA 100 and RMS voltages.
   a. <X> Returns to Probe Calibration Menu.
5. (F2) Calculates the velocities.
6. esc <C>
   a. <S> Values displayed should correspond to those you recorded.
7. esc-esc
8. (F3) Calculates Polynomial Coefficients.
9. esc-esc
10. esc <C>
    a. <L> Displays ambient conditions and calculated Polynomial Coefficients.
11. esc-esc
12. (F7) Saves Documentation.
13. esc <Q> Ends Probe Calibration; Returns to Main Menu.

9. DATA ACQUISITION

1. <A>
2. <F2> Set Experiment File # = 1.
   Set Raw Data File # equal to the number of measurements to be taken.
3. (F1) Acquires data. (Record data manually for each distance.) After data has been taken for the last distance, automatically returns to Data Acquisition Menu.
4. esc <Q> Ends Data Acquisition; Returns to Main Menu.

10. STATISTICAL ANALYSIS

1. <S>
2. (F2) Set Experiment File # = 1.
3. esc <M>
4. (F1) Builds cooling velocity/statistics files.
5. (F2) Set Experiment File # = 1.
6. esc <M>
7. (F3) Press Tab to see first statistical analysis and <N> to advance to next analysis.
8. esc <M>
9. esc <Q> Ends Statistical Analysis; Returns to Main Menu.

11. PROGRAM TERMINATION

1. <Q>

WORKSHEET FOR HOTWIRE MEASUREMENTS

Pa= ______
Ta= ______
Rc= ______
Ro= ______
Rop(given)= ______ Set at: Rop= ______
Bridge Comp set at ______
Eo= ______
Em (fast)= ______

H2O		TEMP deg C	VOLTS	
PITOT	PLE		IFA 100	RMS V/METER
1.	1.	1.	1.	1.
2.	2.	2.	2.	2.
3.	3.	3.	3.	3.
4.	4.	4.	4.	4.
5.	5.	5.	5.	5.
6.	6.	6.	6.	6.

Polynomial Coefficients:
K= ______
A= ______
B= ______
C= ______
D= ______

Endwall Boundary Layer Survey or Hotwire Traverse Measurements
PRESSURE: PITOT ______
PLENUM ______
TEMP ______

X (IN OR DEG)	IFA 100	VOLTS RMS V/METER
1.	1.	1.
2.	2.	2.
3.	3.	3.
4.	4.	4.
5.	5.	5.
6.	6.	6.
7.	7.	7.
8.	8.	8.
9.	9.	9.
10.	10.	10.

APPENDIX B. HOTWIRE INLET ENDWALL BOUNDARY LAYER SURVEY

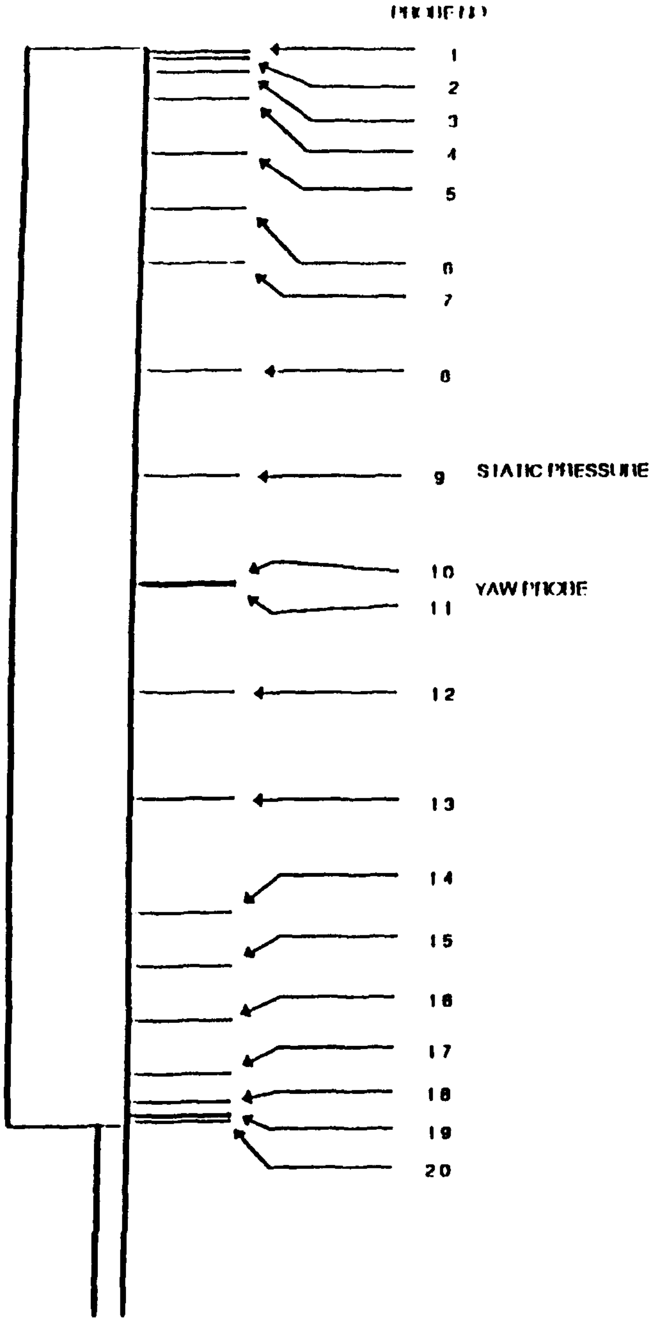
Hotwire measurements were taken, using two methods for different combinations of plenum pressure and suction levels, to establish the freestream turbulence intensity of the cascade tunnel and to show the endwall boundary layer profile.

In the first method, single point measurements were made at the 4-inch spanwise location. Results are shown in Table B1. The mean velocity remained fairly constant and the averaged local turbulence was 1.70%. L denotes low blowing. No suction could not be obtained due to the installation of the porous slots.

In the second method, surveys were made from the north wall to 4 inches in the the spanwise direction. Spanwise measurement stations corresponded to the rake probe locations as shown in Figure B1. Results are shown in Figure B2.

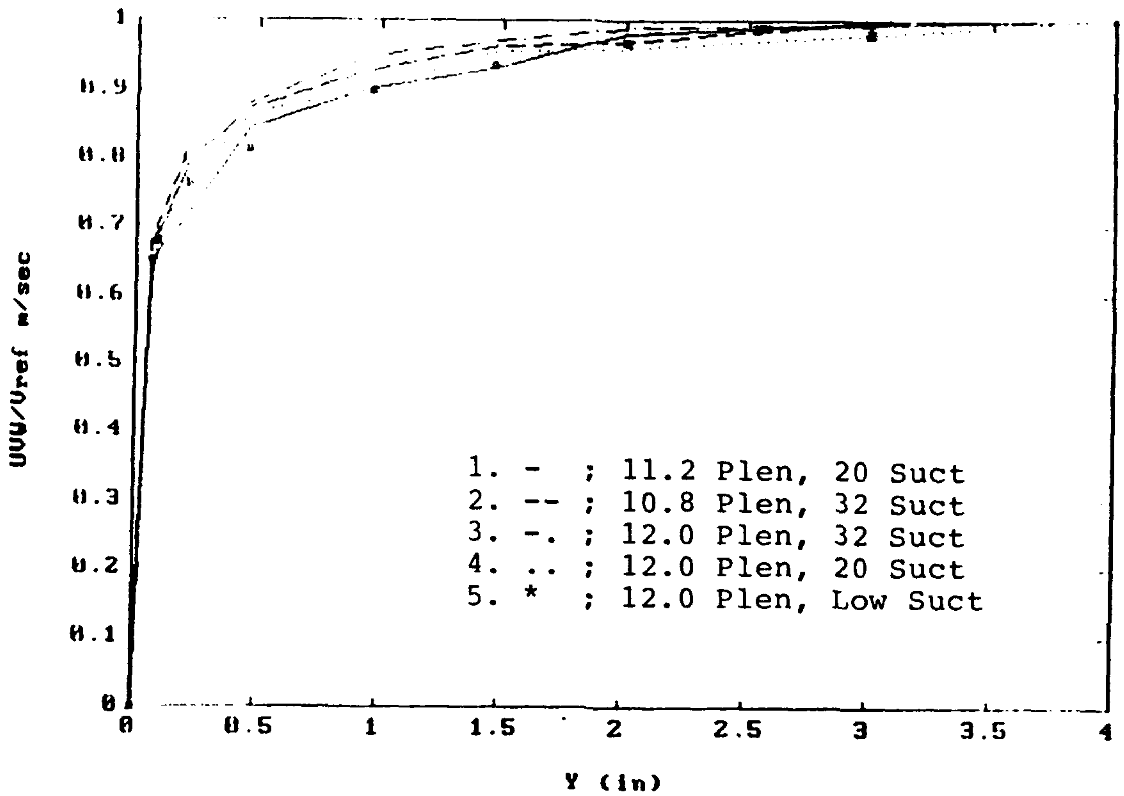
Table B1. Freestream Single Point Measurements

Plen (H2O")	Suction Level (H2O")	Mean Vel (m/sec)	Local Tu (%)
12	L	86.50	1.587
11.5	20	84.77	1.71
11.4	32	83.62	1.61
12	32	87.35	1.99
12	20	88.07	1.62
12	L	88.58	1.55

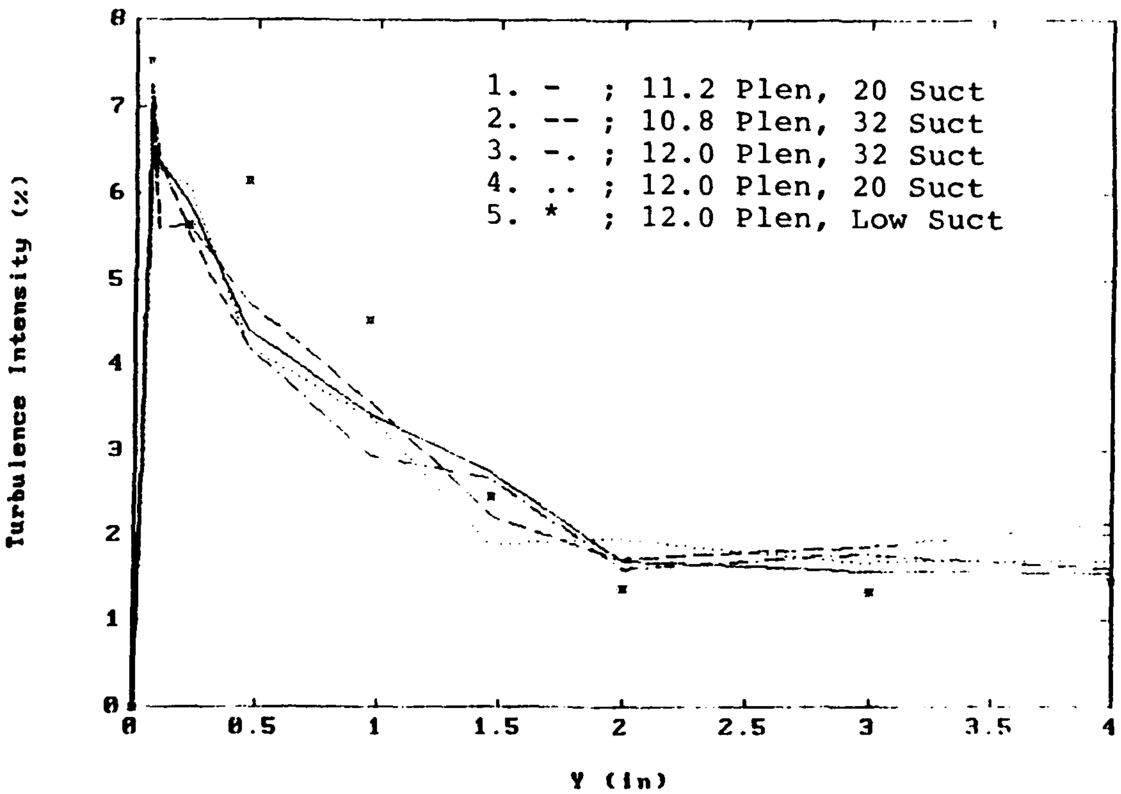


Probe	Location (in)
1.	0.03125
1a.	0.0634
2.	0.09375
3.	0.21875
4.	0.46875
5.	0.96875
6.	1.46875
7.	2.0
8.	3.0
9.	4.0
10.	5.0
11.	5.0
12.	6.0
13.	7.0
14.	8.0
15.	8.5
16.	9.0
17.	9.5
18.	9.7
19.	9.9
20.	10.0

Figure B1. Rake Probe Plan View



a) Non-dimensionalized Velocity



b) Turbulence Intensity

Figure B2. Inlet Endwall Boundary Layer Surveys

APPENDIX C. AXIAL VELOCITY RATIO DATA

To compute the axial velocity ratio, the following procedure documented by Webber [Ref. 11] was used:

$$AVR = \int_0^s \frac{c_{z\,2}}{c_{z\,1}}\,dx$$

where C_z is the axial velocity at the upstream, (1), and downstream, (2), locations and s is one blade pitch (in.). Because of this definition and since the analysis was done for the incompressible case, the local velocity and flow angle measured by the rake probe was used and corrected for by the Prandtl total pressure to compensate for the run-to-run variations. This yielded the following equation:

$$AVR = \int \frac{\sqrt{\left(\left(P_{12} - P_S\right) * \frac{2}{\rho}\right)_2}}{\sqrt{\left(\left(P_{12} - P_S\right) * \frac{2}{\rho}\right)_1}} * \sqrt{\frac{P_{T\,1}}{P_{T\,2}}}\;\frac{Cos(\beta_2)}{Cos(\beta_1)}\,dx$$

where P_T is the corresponding Prandtl total pressure and P_S is from the following equation: $P_{S_{corrected}} = P_S - (0.412 + 0.1817Q)$ This integration was performed by a summation since the interval was held constant. β was measured with the following equation:

$$\beta = \beta_{rake} + \alpha$$

where β_{rake} is the angle the rake probe was mounted in the tunnel, which was 44 degrees for upstream and 90 degrees for downstream, and α is defined on the next page.

$$\alpha = 0.0805 - 31.575 \frac{P_{10} - P_{11}}{Q}.$$

21 October 1993

TABLE C1. 12" H2O Plenum High Suction (72" H2O)
AVR Calculations

Pitch No	Upstrm (f/s)	Pt1	Dwnstrm(a) (f/s)	Pta	Dwnstrm(b) (f/s)	Ptb
1.	200.14	10.55	189.90	10.18	192.479	10.53
2.	199.54	10.64	207.60	10.24	210.819	10.51
3.	200.21	10.68	212.19	10.35	213.281	10.52
4.	199.83	10.61	210.21	10.34	212.716	10.58
5.	199.27	10.66	209.26	10.42	210.099	10.52
6.	195.16	10.69	210.47	10.45	210.069	10.53
7.	199.33	10.72	210.12	10.46	209.148	10.55
8.	198.91	10.78	210.07	10.50	208.982	10.51
9.	199.35	10.72	209.85	10.56	209.123	10.49
10.	198.74	10.77	199.85	10.64	195.424	10.44
11.	198.96	10.83	178.34	10.61	174.905	10.47
12.	198.63	10.81	179.63	10.71	179.811	10.43
13.	198.03	10.77	205.01	10.79	201.452	10.44
Total	2586.11	139.2	2632.52	136.25	2628.32	136.5
Sum Sqrt Pt		42.54		42.08		42.13

$$AVR(a) = \frac{Dwnstrm(a) * Sum\ Sqrt\ Pt1}{Upstrm * Sum\ Sqrt\ Pt(a)} = \frac{2632.5*42.54}{2586.11*42.08} = 1.029$$

$$AVR(b) = \frac{Dwnstrm(b) * Sum\ Sqrt\ Pt1}{Upstrm * Sum\ Sqrt\ Pt(b)} = \frac{2628.3*42.54}{2586.1*42.13} = 1.026$$

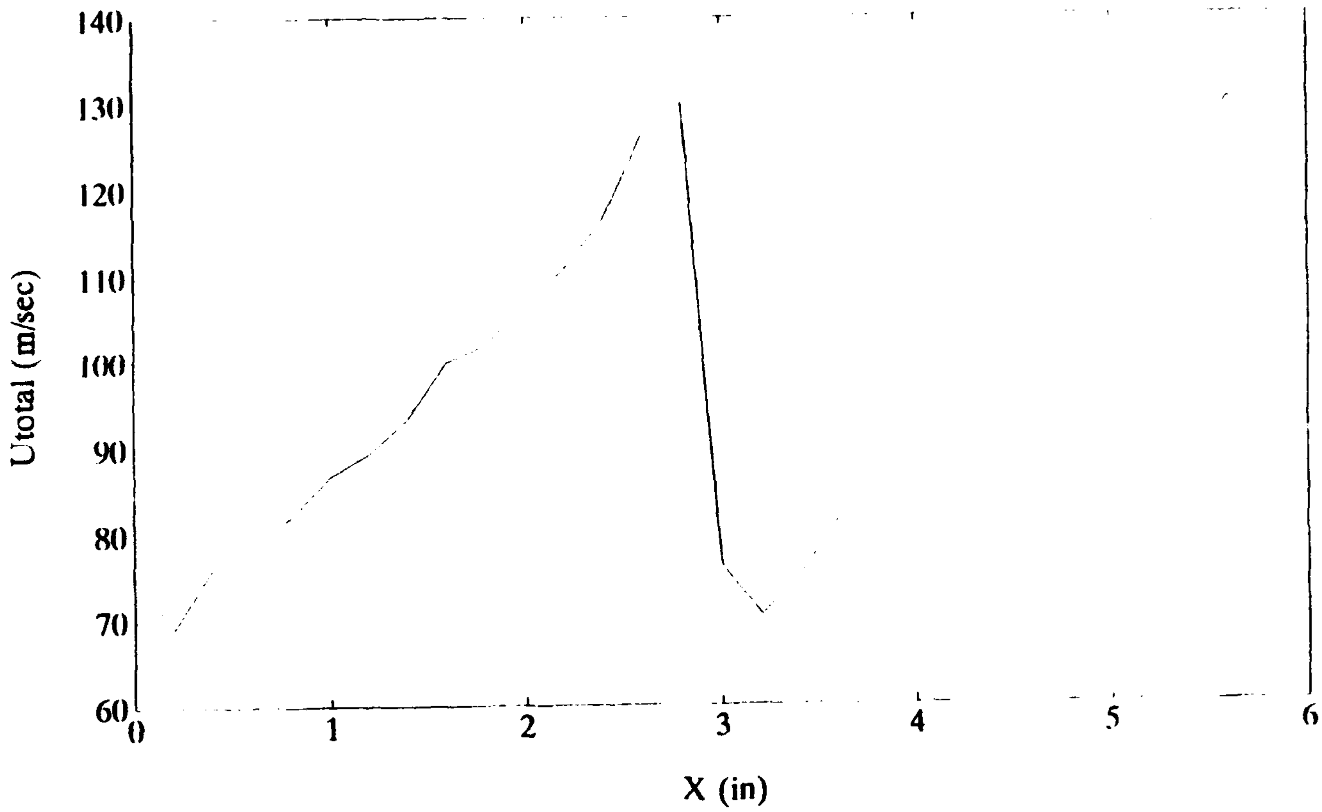
APPENDIX D. HOTFILM PITCHWISE AND ROTATED SURVEYS

Additional hotfilm data are provided below. These data show repeatability in data measurements and technique.

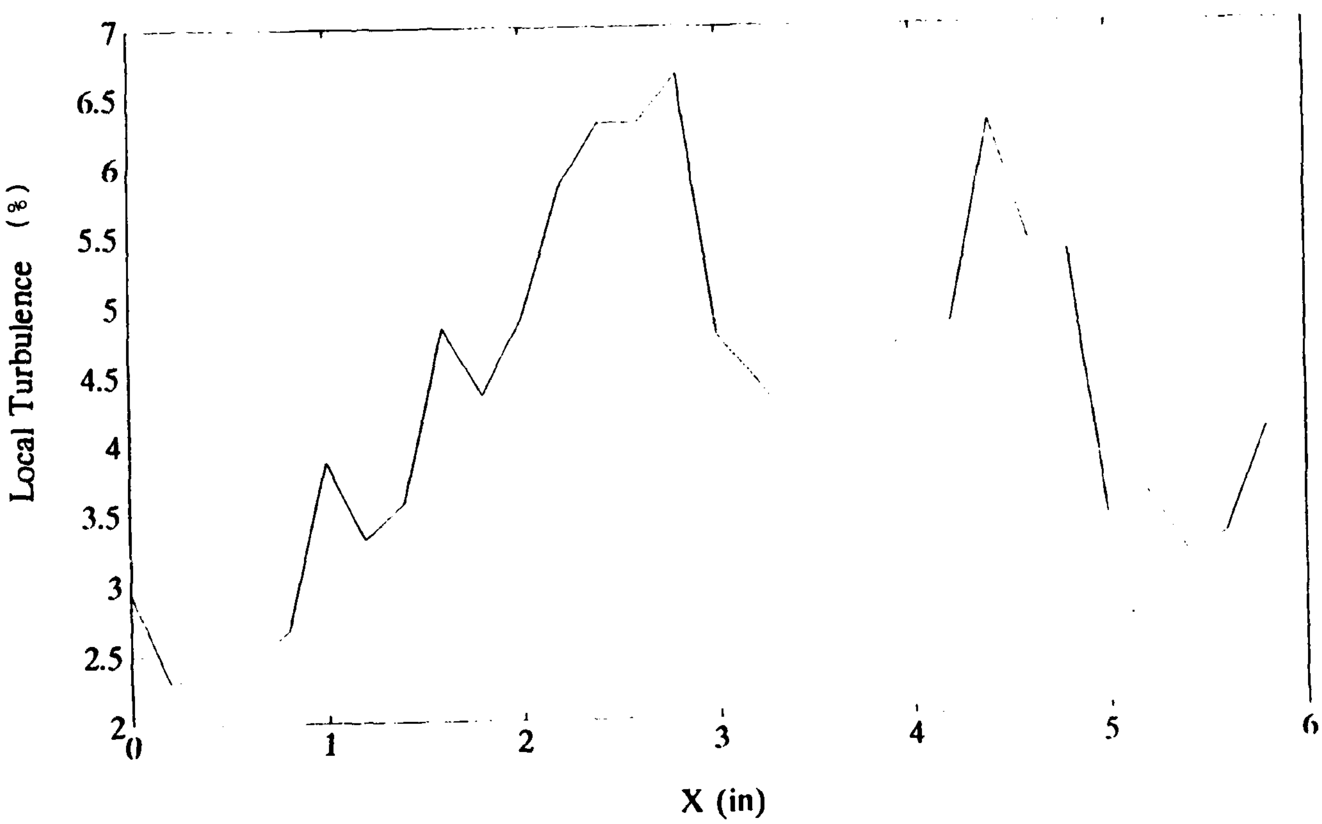
TABLE D1. UPPER SLOT PITCHWISE TRAVERSE BETWEEN BLADES 8 & 6

HOTWIRE29 18NOV93

X (in)	Utotal (m/s)	Local Tu (%)
0	74.955	2.9373
.2	69.142	2.2915
.4	76.062	2.3459
.6	78.711	2.4212
.8	82.159	2.6687
1.0	86.845	3.8577
1.2	89.361	3.3015
1.4	93.462	3.5658
1.6	99.969	4.8308
1.8	102.09	4.3423
2.0	106.78	4.8832
2.2	110.79	5.8376
2.4	116.53	6.2972
2.6	126.31	6.2923
2.8	129.93	6.6413
3.0	76.331	4.7641
3.2	70.336	4.4230
3.4	75.053	4.0723
3.6	81.349	4.2192
3.8	84.822	4.4360
4.0	87.311	4.8247
4.2	91.362	4.8281
4.4	96.521	6.2779
4.6	100.54	5.4277
4.8	105.56	5.3378
5.0	109.77	3.3928
5.2	115.31	3.5763
5.4	123.35	3.1490
5.6	130.32	3.2683
5.8	127.67	4.0240



a) Total Velocity



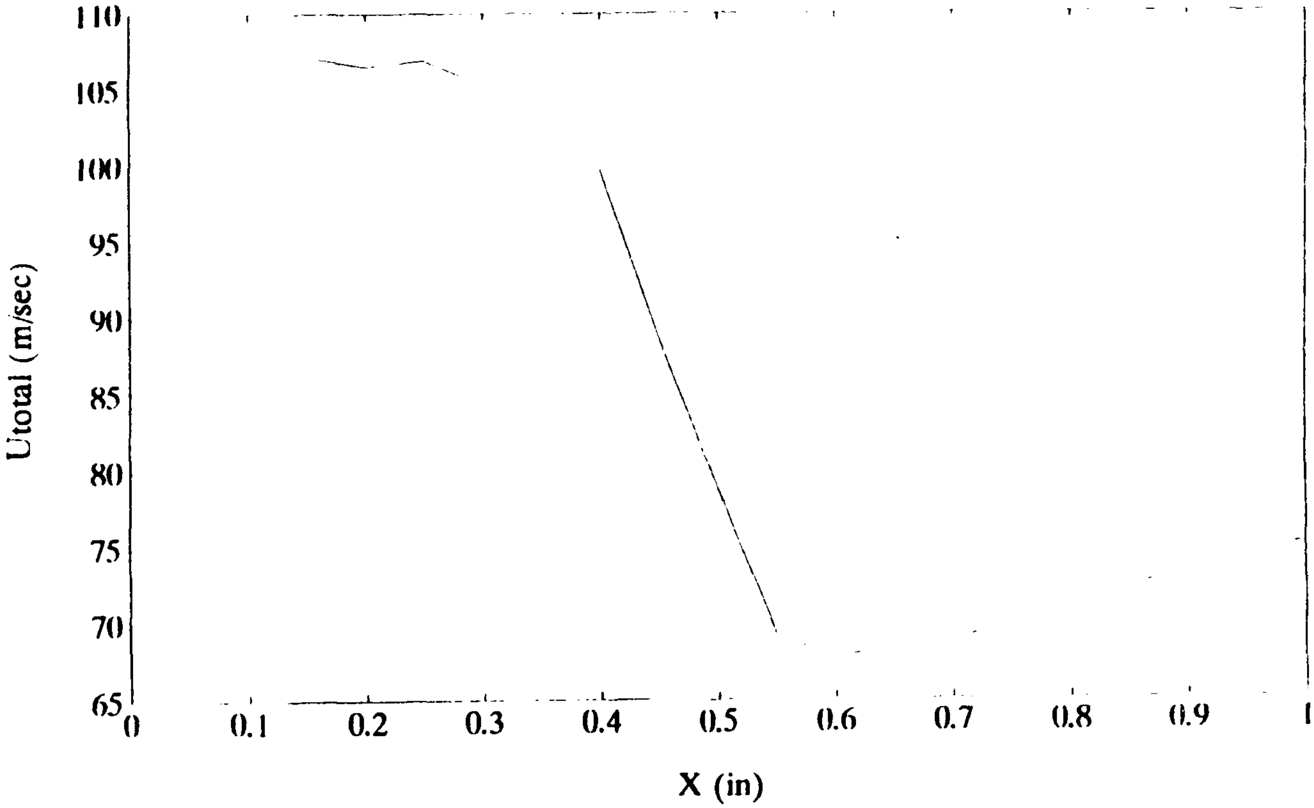
b) Local Turbulence

Figure D1. Upper Slot Pitchwise Traverse; Blades 8-6

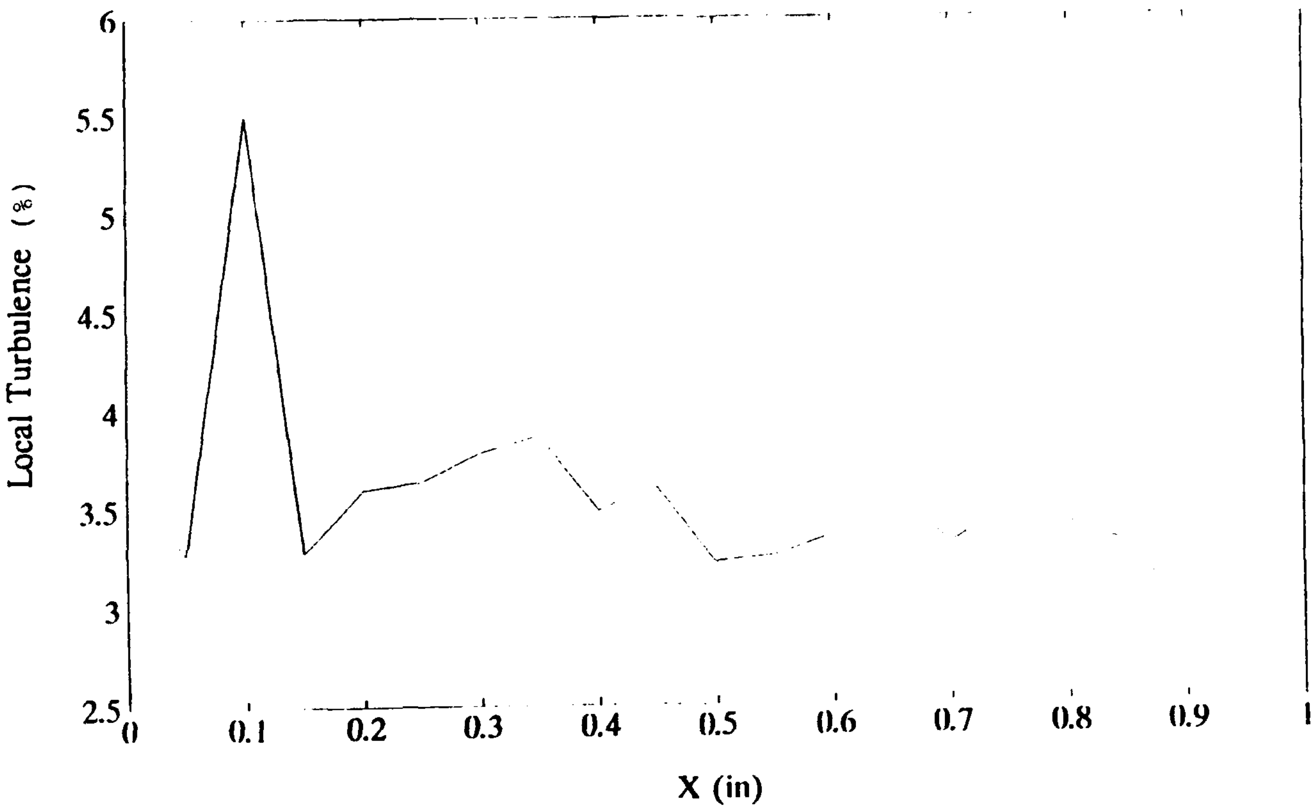
TABLE D2. UPPER SLOT PITCHWISE TRAVERSE BLADE 7 (+ or - .5")

HOTWIRE30 18NOV93

X (in) (in)	Utotal (m/s)	Local Tu (%)
0	104.486	3.6591
.05	106.400	3.2784
.1	104.319	5.5046
.15	107.152	3.2840
.2	106.542	3.5993
.25	106.912	3.6396
.3	105.337	3.7851
.35	102.361	3.8685
.4	99.7501	3.4905
.45	88.5520	3.5989
.5	78.8000	3.2258
.55	69.1020	3.2557
.6	67.8005	3.3579
.65	68.1636	3.5735
.7	68.8390	3.3110
.75	69.8337	3.5104
.8	70.2995	3.4095
.85	72.1923	3.3018
.9	73.3852	2.9472
.95	74.5954	2.8255
1.0	75.1441	2.5724



a) Total Velocity

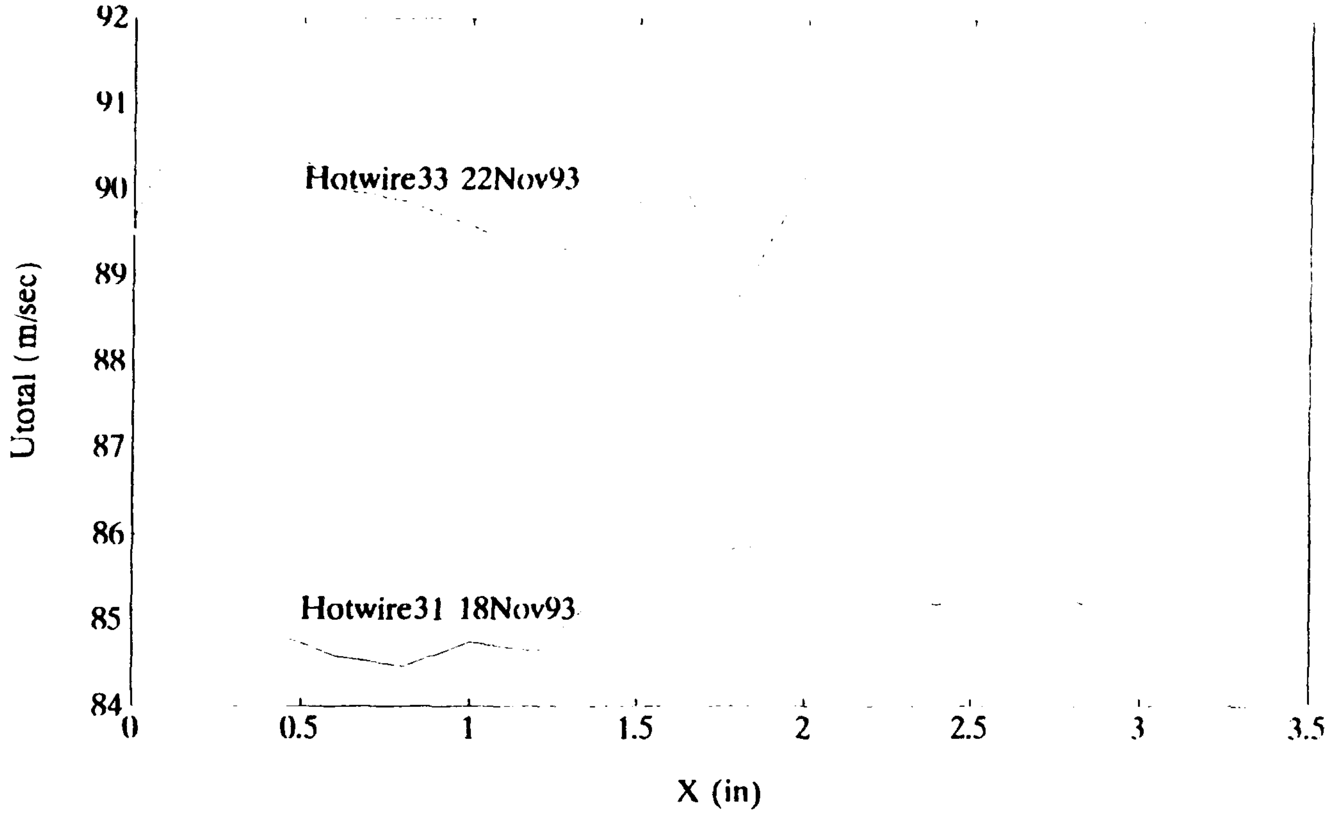


b) Local Turbulence

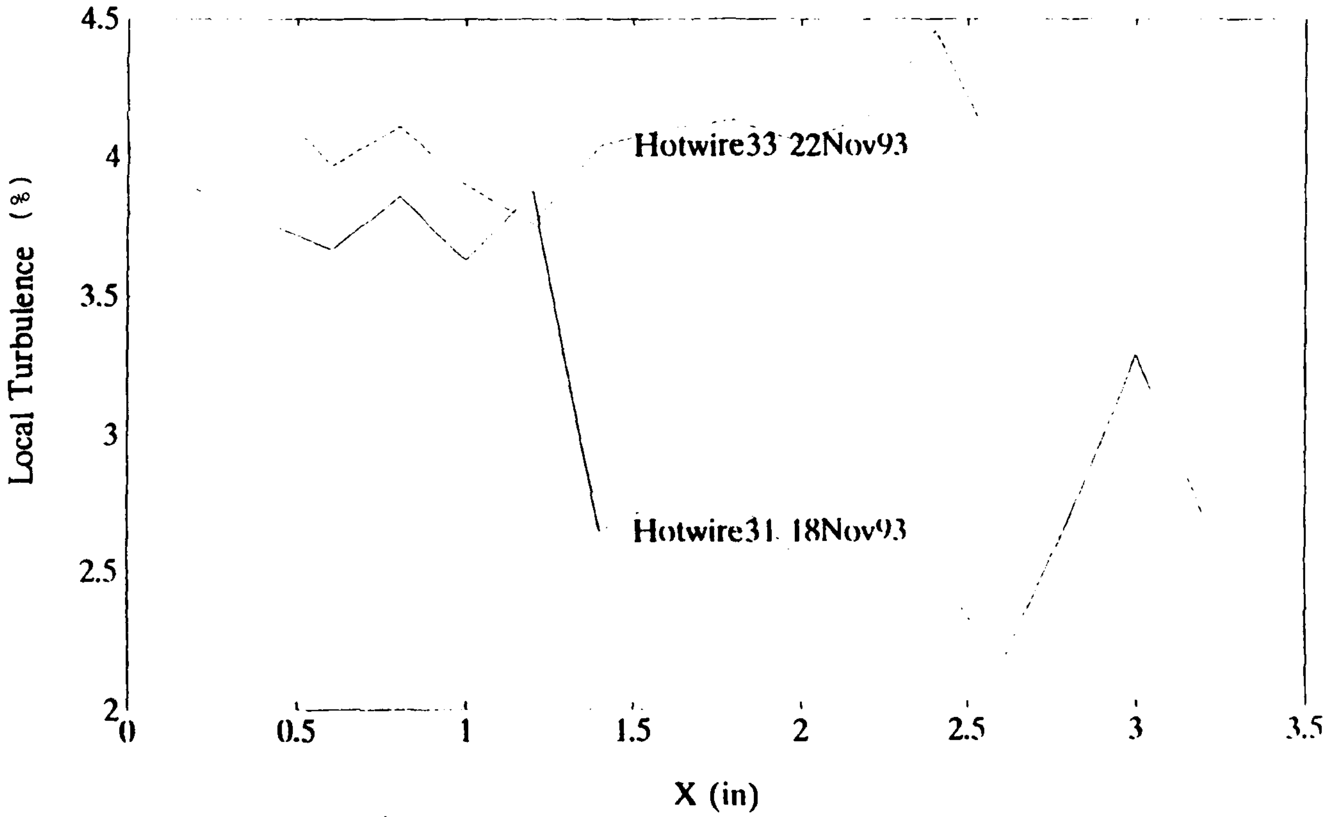
Figure D2. Upper Slot Pitchwise Traverse; Blades 8-7

TABLE D3. LOWER SLOT PITCHWISE TRAVERSE BETWEEN BLADES 8 & 7

	HOTWIRE31 18NOV93		HOTWIRE33 22NOV93	
X (IN)	Utotal (m/s)	Local Tu (%)	Utotal (m/s)	Local Tu (%)
0	85.076	3.799	89.730	4.030
.2	85.476	3.886	91.068	4.093
.4	84.879	3.766	90.662	4.223
.6	84.577	3.666	90.022	3.969
.8	84.455	3.860	89.870	4.111
1.0	84.745	3.632	89.591	3.900
1.2	84.628	3.876	89.235	3.762
1.4	85.317	2.637	89.404	4.039
1.6	85.481	2.759	90.327	4.101
1.8	85.848	2.759	88.730	4.133
2.0	85.839	2.542	90.184	4.051
2.2	85.241	2.588	89.780	4.145
2.4	85.184	2.500	89.564	4.456
2.6	85.280	2.162	90.735	3.965
2.8	85.244	2.677	90.390	3.940
3.0	84.880	3.285	89.897	3.934
3.2	85.361	2.695	89.810	3.927



a) Total Velocity



b) Local Turbulence

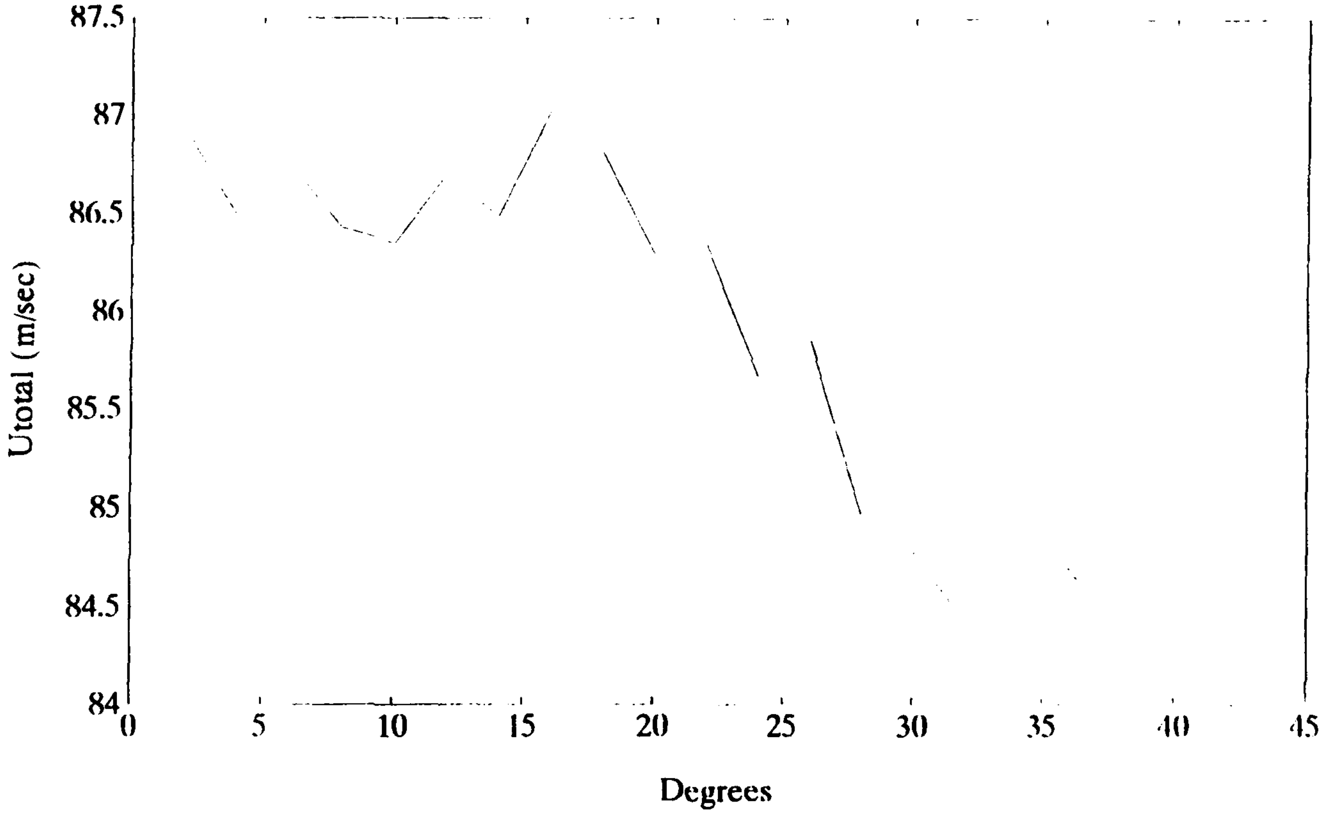
Figure D3. Lower Slot Pitchwise Traverse; Blades 8-7

TABLE D4. ROTATED PROBE FROM HORIZONTAL TO INLET FLOW ANGLE

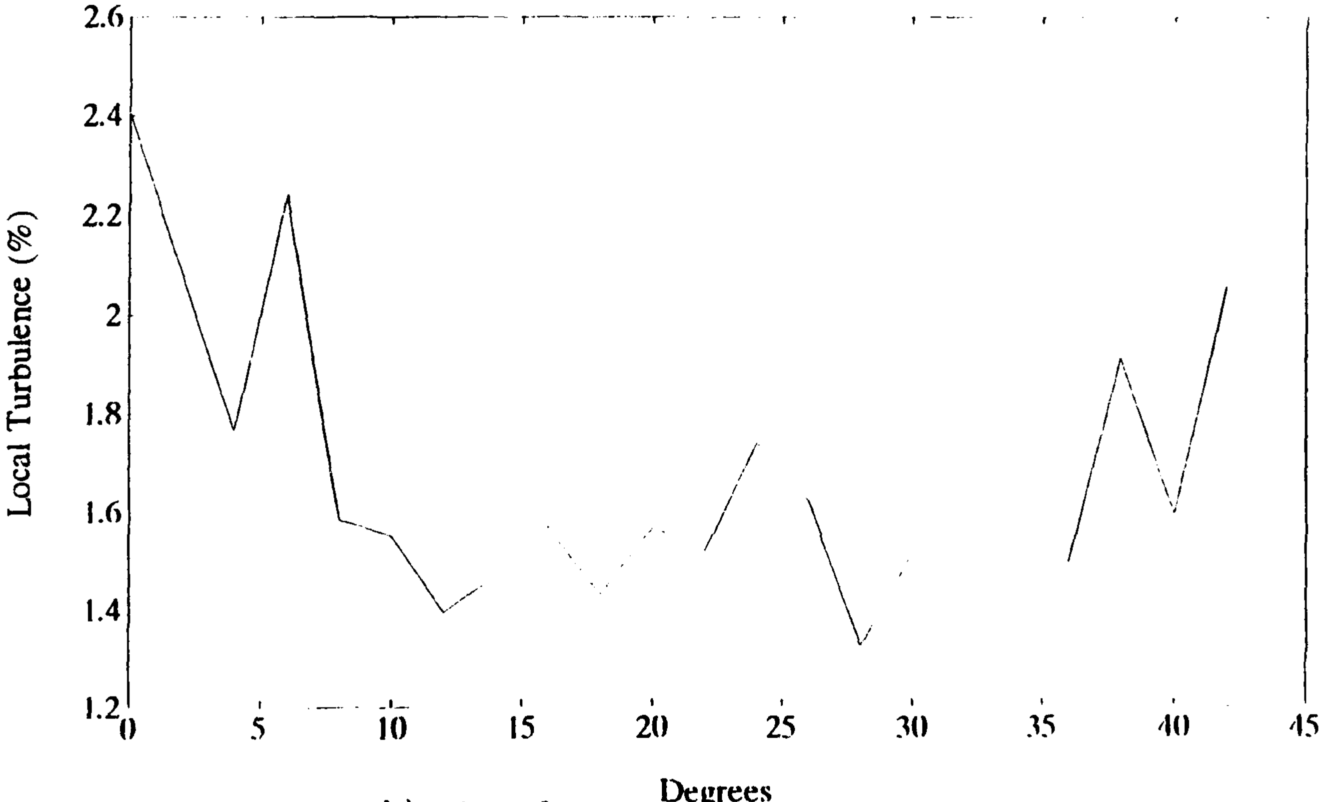
A. AT LEADING EDGE OF BLADE 7

HOTWIRE32 18NOV93

Deg	Utotal (m/s)	Local Tu (%)
0	87.113	2.407
2	86.935	2.084
4	86.490	1.764
6	86.758	2.242
8	86.429	1.583
10	86.347	1.551
12	86.693	1.395
14	86.483	1.470
16	87.019	1.567
18	86.817	1.431
20	86.288	1.565
22	86.352	1.516
24	85.659	1.740
26	85.854	1.620
28	84.965	1.324
30	84.776	1.513
32	84.430	1.577
34	84.709	1.483
36	84.693	1.495
38	84.376	1.910
40	84.486	1.592
42	84.223	2.055



a) Total Velocity



b) Local Turbulence

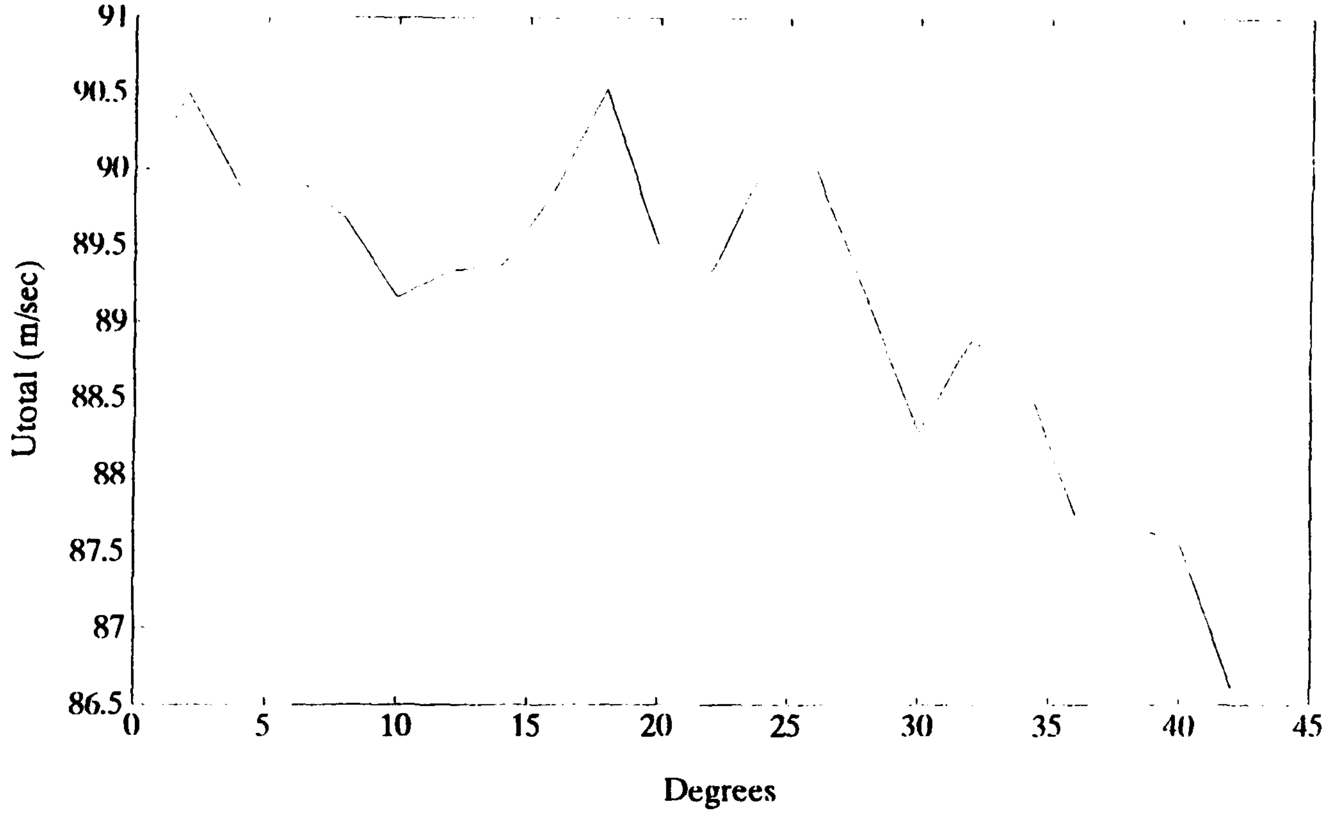
Figure D4a. Rotated From Horizontal To Inlet Flow Angle

TABLE D4. ROTATED PROBE FROM HORIZONTAL TO INLET FLOW ANGLE

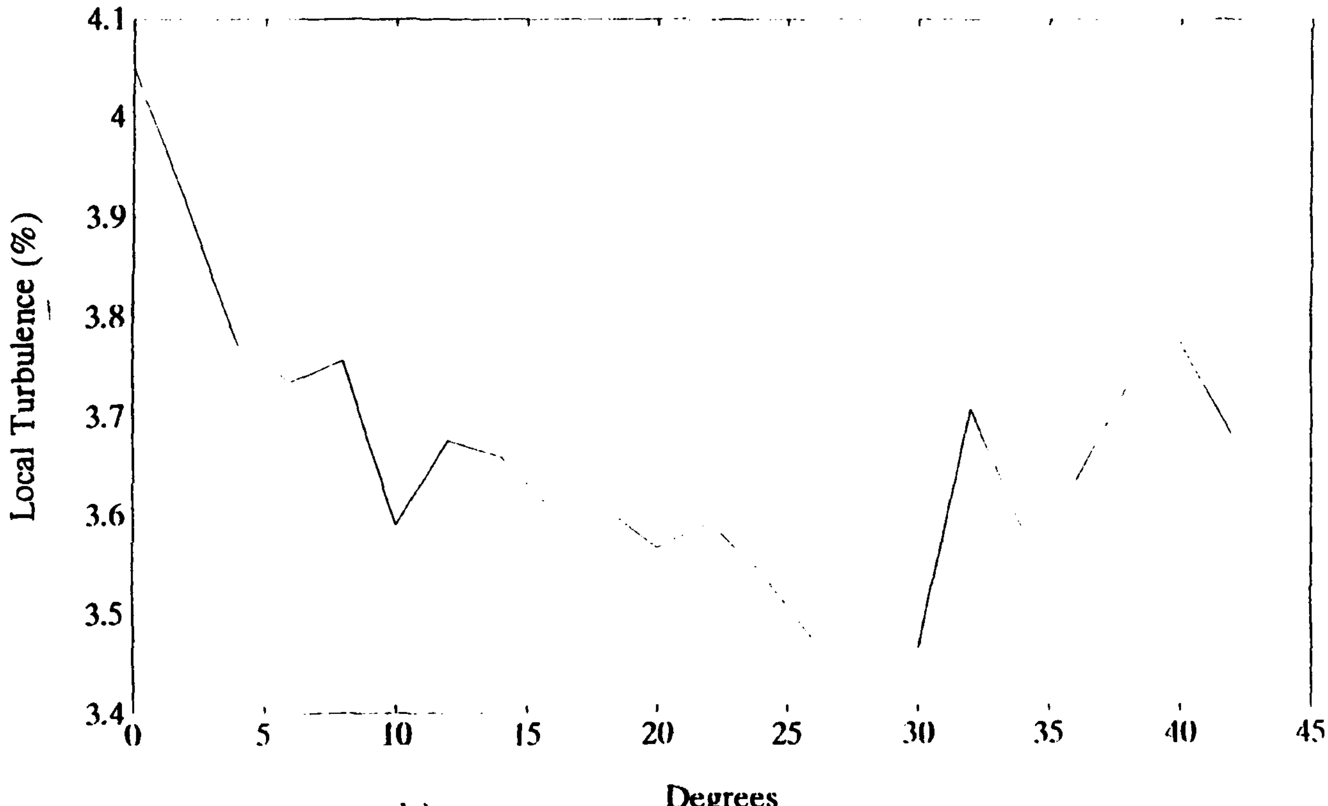
B. MIDWAY BETWEEN BLADES 7 & 8

HOTWIRE34 22NOV93

Deg	**Utotal (m/s)**	**Local Tu (%)**
0	89.857	4.050
2	90.469	3.912
4	89.877	3.772
6	89.961	3.735
8	89.682	3.756
10	89.157	3.589
12	89.333	3.676
14	89.374	3.659
16	89.852	3.605
18	90.532	3.606
20	89.501	3.566
22	89.320	3.591
24	90.006	3.541
26	90.006	3.472
28	89.160	3.510
30	88.283	3.465
32	88.889	3.707
34	88.670	3.584
36	87.740	3.633
38	87.682	3.730
40	87.562	3.774
42	86.605	3.680



a) Total Velocity



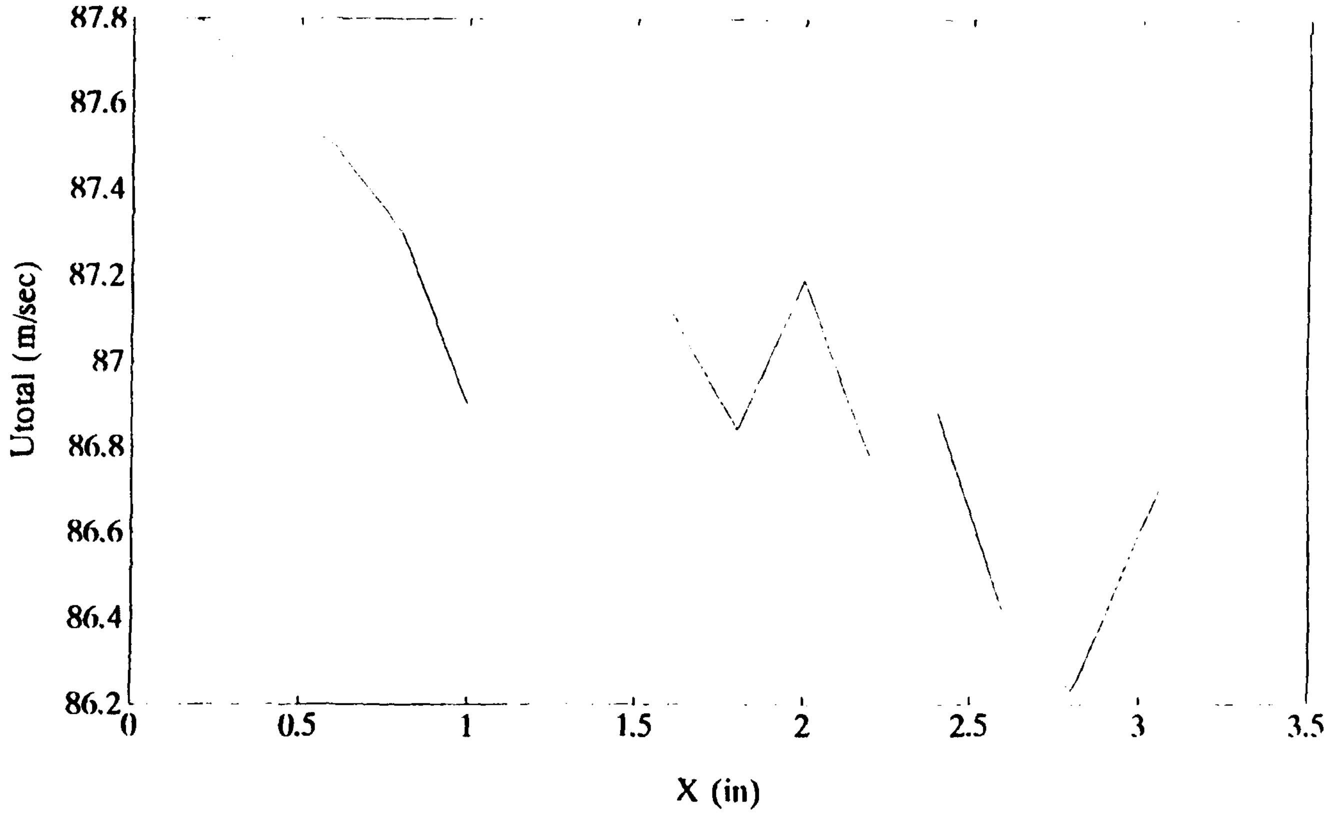
b) Local Turbulence

Figure D4b. Rotated From Horizontal To Inlet Flow Angle

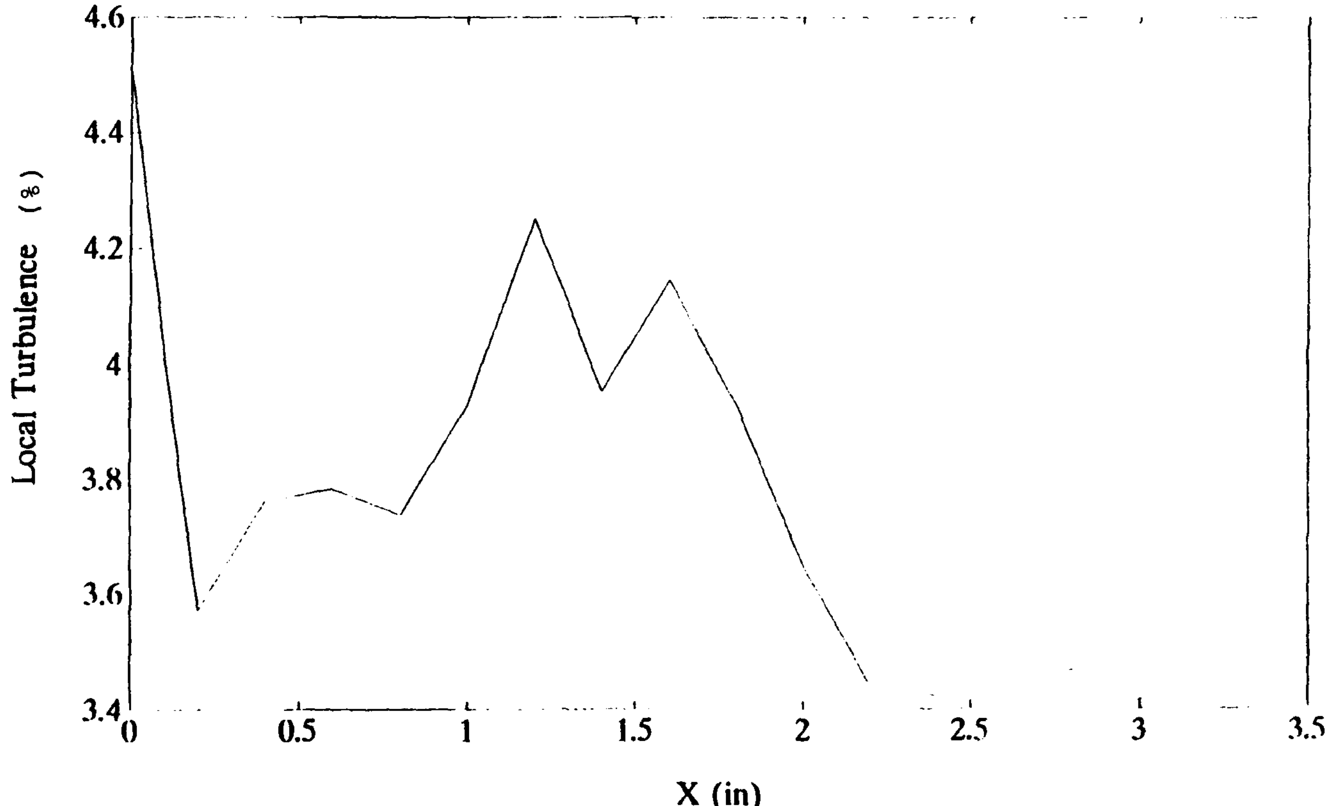
TABLE D5. PITCHWISE TRAVERSE WITH PROBE AT INLET FLOW ANGLE BETWEEN BLADES 8 & 7

HOTWIRE35 22NOV93

X (in)	Utotal (m/s)	Local Tu (%)
0	87.672	4.511
.2	87.807	3.569
.4	87.612	3.756
.6	87.502	3.782
.8	87.277	3.737
1.0	86.960	3.928
1.2	86.997	4.251
1.4	87.106	3.951
1.6	87.119	4.143
1.8	86.839	3.928
2.0	87.192	3.647
2.2	86.770	3.440
2.4	86.875	3.423
2.6	86.436	3.433
2.8	86.226	3.468
3.0	86.607	3.415
3.2	86.936	3.480



a) Total Velocity

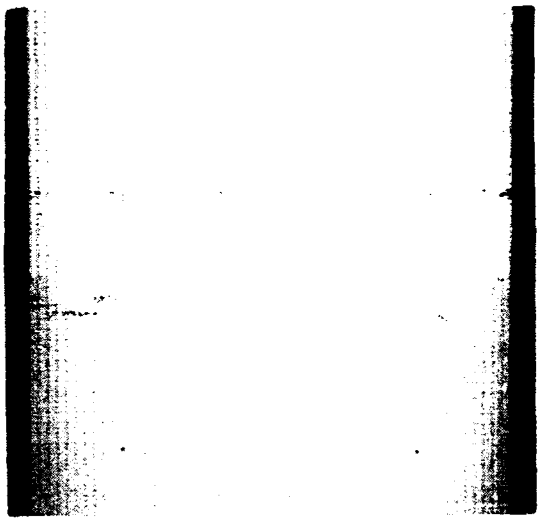


b) Local Turbulence

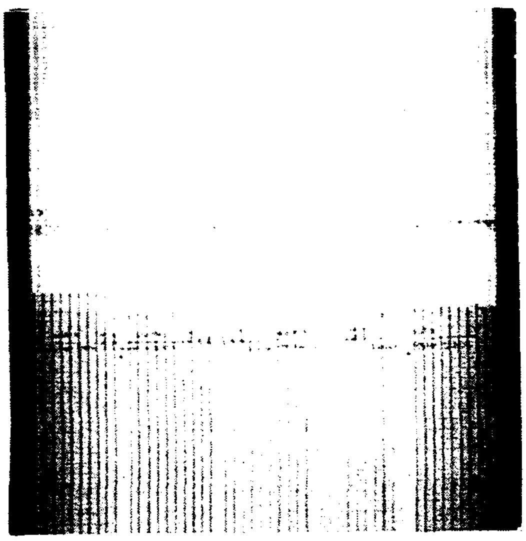
Figure D5. Lower Slot Pitchwise Traverse At Inlet Flow Angle Between Blades 8 & 7

APPENDIX E. ENDWALL STATIC PRESSURES

The manometer data were taken by marking the tubes during the test conducted at 48 degree inlet flow angle and recorded at completion. Polaroid pictures were also taken during the tests and examples are presented here.



a) Upstream Manometer Bank



b) Downstream Manometer Bank

Figure E1. Endwall Static Pressures

LIST OF REFERENCES

1. Walraevens, R.E, and Cumpsty, N.A., Leading Edge Separation Bubbles on Turbomachine Blades, ASME paper 93-GT-91, presented at the International Gas Turbine and Aeroengine Congress and Exposition, Cincinnati, Ohio, May 24-27,1993.

2. Gostelow, J.P., Cascade Aerodynamics, 1st Ed., Permagon Press, 1984.

3. NASA Technical Memorandum 82763, The Use of Optimization Technique to Design C-D Compressor Blading, by N.L. Sanger, Lewis Research Center, Cleveland, Ohio, 1982.

4. Koyuncu, Y., Report of Tests of a Compressor Configuration of CD Blading, Master's Thesis, Naval Postgraduate School, Monterey, California, March 1984.

5. Dreon, J., Controlled Diffusion Compressor Blade Wake Measurements, Master's Thesis, Naval Postgraduate School, Monetery, California, September 1986.

6. Elazar, Y., A Mapping of the Viscous Flow Behavior in a Controlled Diffusion Compressor Cascade Using Laser Doppler Velocimetry and Preliminary Evaluation of Codes for the Prediction of Stall, Ph. D. Dissertation, Naval Postgraduate School, Monterey, California, March 1988.

7. Baydar, A., Hot-wire Measurements of Compressor Blade Wakes in a Cascade Wind Tunnel, Master's Thesis, Naval Postgraduate School, Monterey, California, March 1988.

8. Classick, M., Off-Design Loss Measurements in a Compressor Cascade, Master's Thesis, Naval Postgraduate School, Monterey, California, September 1989.

9. Armstrong, J.H., Near-Stall Loss Measurements in a CD Compressor Cascade with Exploratory Leading Edge Flow Control, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1990.

10. Hobson, G.V. and Shreeve, R.P., Inlet Turbulence Distortion and Viscous Flow Development in a Controlled-Diffusion Compressor Cascade at Very High Incidence, AIAA paper 91-2004 presented at the 27th Joint Propulsion Conference, Sacramento, California, June 24-26,1991.

11. Webber, M.A., Determining the Effects of Endwall Boundary Layer Suction in a Large Scale Subsonic Compressor Cascade, Master's Thesis, Naval Postgraduate School, Monterey, California, March 1993.

12. Sanger, N.L. and Shreeve, R.P., "Comparison of Calculated and Experimental Cascade Performance for Controlled-Diffusion Stator Blading," Journal of Turbomachinery, July 1986, pp. 42-50.

13. Murray, K., Automation and Extension of LDV Measurements of Off-Design Flow in a Subsonic Cascade Wind Tunnel, A.E. Thesis, Naval Postgraduate School, Monterey, California, June 1989.

14. TSI Company, Model DAP-Thermal Anemometry Software, St. Paul Minnesota, January 1993.

15. TSI Company, IFA 100 Intelligent Flow Analyzer Instruction Manual, St. Paul, Minnesota, August 1993.

16. Horlock, J.H., Axial Flow Compressors, Krieger Publishing Company, 1958, pp.73-75.

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